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USER'S MANUAL FOR CORHYD: AN INTERNAL DIFFUSER HYDRAULICS MODEL

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USER'S MANUAL FOR CORHYD: AN INTERNAL DIFFUSER HYDRAULICS MODEL

by

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Abstract

Submerged multiport diffusers for waste water outfalls are designed often, considering steady flow conditions for far future scenarios. Design aims for lower costs for material use and pumping energy and the minimization of environmental impacts. Inadequate attention on the internal diffuser hydraulics also for off design conditions thereby often result in hydraulic problems like partial blockage, high head losses, uneven flow distribution, salt water intrusion and poor dilution causing higher energy demands and stronger environmental impacts.

The CorHyd computer program has been developed for the calculation of velocities, pressures, head losses and flow rates inside the diffuser pipe and, especially, at the diffuser port orifices to analyze and optimize diffuser design alternatives as well as existing diffuser configurations for different and varying discharge and ambient conditions. The calculation is based on the application of the steady continuity and work-energy equations between ambient fluid at the discharge points and the effluent inside the diffuser pipe. Emphasis was given to the implementation of all occurring losses especially if high risers, duckbill valves, multiple ports and more complex discharge configurations are applied.

Detailed calculations for the internal manifold hydraulics in the outfall pipes show a strong sensitivity on the representation and formulation of local losses even for relatively simple riser/port configurations. An optimization methodology yields a homogeneous discharge distribution along the diffuser, minimization of the total head and prevention of sedimentation or ambient water intrusion in the diffuser under varying inflow and ambient conditions. The final design achieves lower costs for material use and operation as well as the minimization of environmental impacts and operational stability for off-design conditions.

Acknowledgments

The authors like to express their gratitude to the student assistants Martina Kurzke and Jan Müller who contributed to the coding of the present program. Thanks to Rob Doneker from Mixzon Inc. for his friendly and scientific help and the offer to include the program in CORMIX, the Cornell Mixing Zone Expert System. We furthermore appreciated the data support from TideFlex Technologies from RedValve Company and Elasto-Valve Rubber Products (EVR) company for developing loss formulations for duckbill valves.

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Glossary

Table 1: Summary of parameters, Parameters are used with the following major indices: d = diffuser pipeline section; p = port pipe; j = jet

Parameter	Dimension	Definition
ρ_a	kg/m³	average density of ambient water body
ρ_e	kg/m³	average density of the effluent
A	m²	pipe cross sectional area
B	m	equivalent slot width $B = A_p/l$
C_c	-	jet contraction coefficient
D	m	internal pipe diameter
E	m	energy head
g'	m/s²	reduced gravity, $g' = \Delta\rho/\rho g$
H	m	head above datum (additional indices: H_t = total head at headworks; H_d = design water level elevation of ambient water)
i	-	numbering of port/riser configurations (counting from seaward end to shore, starting with 1)
j	-	numbering of local losses in ports, risers or the diffuser
j_0	m³/s³	buoyancy flux per diffuser length, $j_0=g'q_0$
k_s	m	equivalent sand roughness
l	m	riser spacing
L	m	length of the considered pipe section
n	-	total number of local losses j in between one pipe section
N	-	total number of port/riser locations i of diffuser
N_d	-	total number of diffuser sections (includes feeder)
N_g	-	total number of port/riser groups
N_{gp}	-	number of risers per group
N_p	-	number of ports per riser
p	Pa = N/m²	pressure, (additional indices: p_l = pressure loss, p_a = ambient water pressure)
Q	m³/s	total flow through outfall system
q	m³/s	individual discharge through a riser or port at position i
q_0	m²/s	mass flux per diffuser length , $q_0 = V_jB$
R	m	radius of bend
Re	-	Reynolds number $Re = VD/\nu$
S_c	-	plume centerline dilution
SecNo	-	diffuser segment number where this group is located in
t	s	time
V	m/s	mean flow velocity
x	m	horizontal coordinate of pipe segment centerline location
y	m	horizontal coordinate of pipe segment centerline location
z	m	position or elevation in the vertical
α_i	-	1 / (number of ports at a riser at position i)
β	°	angle of gradual expansion or contraction
ζ	-	dimensionless loss coefficient for local losses
λ	-	dimensionless friction coefficient
ν	m²/s	kinematic viscosity

1 Introduction

CorHyd is a computer code for the calculation of flow characteristics in multiport diffuser constructions. It includes loss calculations for complex geometries, as well as additional flow forcing due to density differences.

CorHyd is a code written within the commercial software MatLab Release 14 from the company Mathworks. The code includes a graphical user interface and allows to use all MatLab functions for graphics, analysis and also further modifications. CorHyd is no self-executable and needs MatLab to be installed. But also open source softwares like Scilab (http://scilabsoft.inria.fr/) or Octave (http://www.octave.org) allow to import and execute the MatLab based CorHyd files. CorHyd is an open source code and allows for easy modifications. Downloads of the code and this manual, as well as further information are available under: http://www.cormix.de/corhyd.htm.

An additional version is foreseen to be included into CORMIX (Cornell Mixing Zone Expert System from MixZon, www.cormix.info). It is based on the same algorithm and includes the same loss formulations, but uses the CORMIX interface and allows for easy data transfer between an external hydraulics calculation with CORMIX and the internal hydraulics calculation with CorHyd.

Publications from Bleninger et.al, 2002 and Bleninger et.al, 2005 describe scientific basis and demonstrate comparisons and validation.

The objectives of this manual are: a) to provide comprehensive description of CorHyd, b) give guidance for assembly and preparation of required input data, c) delineate ranges of applicability, d) guidance for interpretation of results, and e) to illustrate practical application.

1.1 Installation and start

Unzip the matlab files into one folder on your computer. Run Matlab and change to the folder, where the files have been saved as your working directory. Type IDH and the graphical user interface opens up. Open an existing test file and press run to do the first calculation.

2 Background

2.1 Multiport diffusers

Waste water treatment plants commonly discharge treated effluents through outfalls into rivers or coastal waters. These plants are designed to minimize environmental impacts by reducing the pollutant concentrations of the effluent. Nevertheless, even discharges of state-of-the-art treatment plants may cause local pollution of the receiving waters, if the effluent contains persistent substances and especially if discharge flowrates are high, which is the case for most large metropolitan areas (like Buenos Aires, New York, Rio de Janeiro, HongKong, Boston, Istanbul, …). To prevent local pollution and to protect ecologically sensitive regions, persistent substances have to be reduced directly at the source and the large discharges have to be distributed over a wider area. For the latter purpose, long outfall pipes with multiport diffuser installations are used to disperse the effluent to non-critical levels (Jirka and Lee, 1994), aided by the natural pollution degradation rates of the receiving water bodies.

An optimized combination of on-land treatment and receiving water capacities, especially for nutrient inputs from municipal sources, may positively affect the world's severe health problems often directly caused by sanitation problems (UNEP, 2004). New water quality regulations (e.g., US: EPA, 1994; Europe: EC-Water framework directive, 2000; Brazil: CONAMA, 2000; Argentina / Uruguay: Guarga et al. 1992) account for that combined approach and therefore also result in a worldwide increasing utilization of treatment plants with multiport diffuser outfalls (e.g., Australia: Philip and Pritchard, 1996; USA: Signell et al., 2000).

An outfall is a pipe system between the dry land and the receiving water. It consists of three components (Fig. 1): the *onshore headwork* (e.g. gravity or pumping basin); the *feeder pipeline* which conveys the effluent to the disposal area; and the *diffuser section,* where a set of ports releases and disperses the effluent into the environment to minimize the impacts on the quality of the receiving water body. Diffusers can be single branched or double branched systems (T- or Y-shaped, Fig. 2). If the the diffuser section is simply laid on the sea bed it is composed of port orifices in the wall of the diffuser pipe (simple port configuration, Fig. 3a), which may carry additional elements like elastic, variable area orifices (duckbill valves, Fig. 3b). If diffusers are covered with ballast, laid in a trench or even tunneled in the ocean floor vertical risers (riser/port configuration, Fig. 3c) are connected to the diffuser to convey the effluent to the water body. For deep tunneled solutions often rosette-like port arrangements (similar to a gas burner device, Fig. 3d) are used to save the number of risers and allow for increased dispersion. Also risers may carry duckbill valves, which change their effective open port area related to the pressure difference between inside and outside the valve. They avoid salt water intrusion during low flow periods and allow high discharges during peak flow periods.

The flow in multiport diffusers is controlled by two boundary conditions: first, the entrance boundary (flow rate or head), and, second, the ambient/disposal boundary, where the effluent physical properties differ from the ambient fluid. Both conditions vary in time due to discharge variations (diurnal changes, storm water events and long-term changes due to increased sanitation coverage) and pressure variations, density variations, tides or waves.

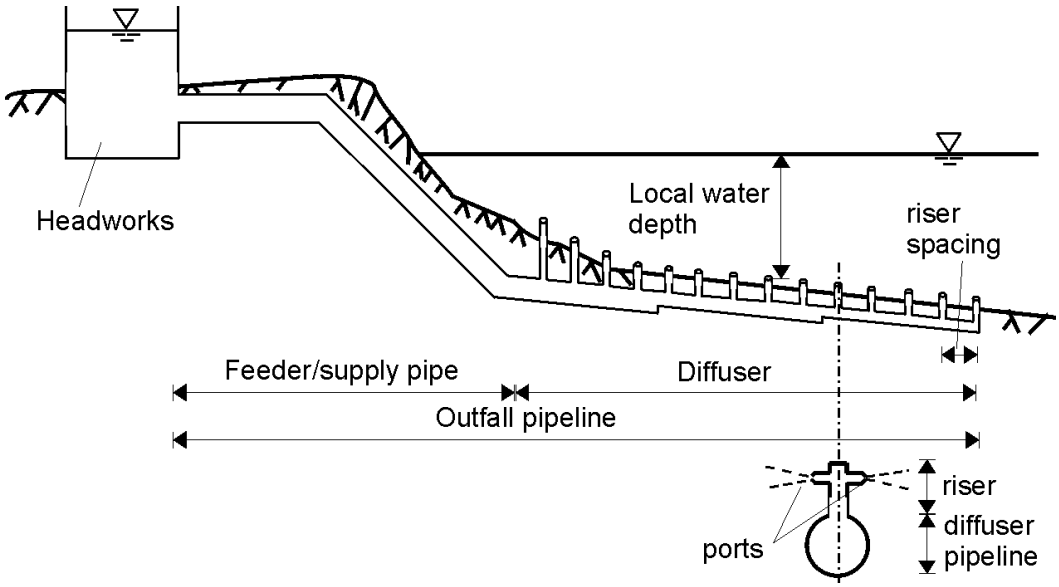


Fig. 1: Outfall configuration showing feeder pipe and diffuser from side view and top view, defining the pipelines and port/riser configurations

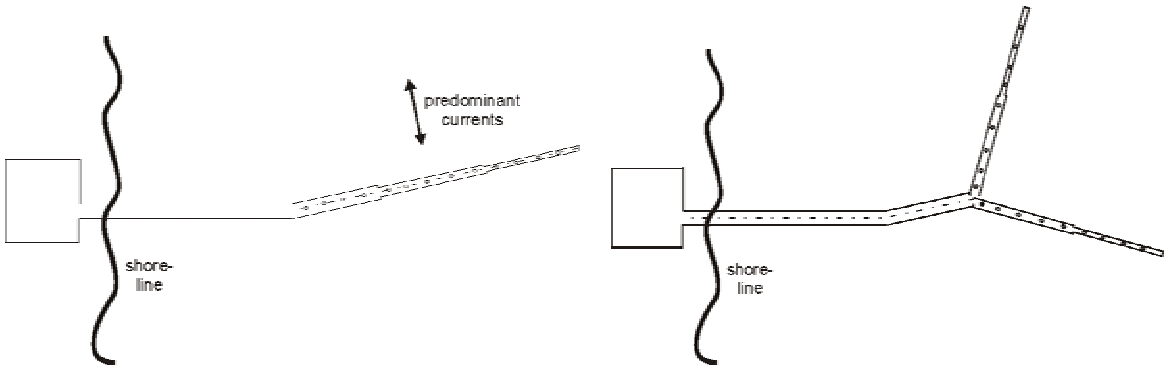


Fig. 2: Left: standard diffuser, Right: Y- or T-shape diffuser configuration

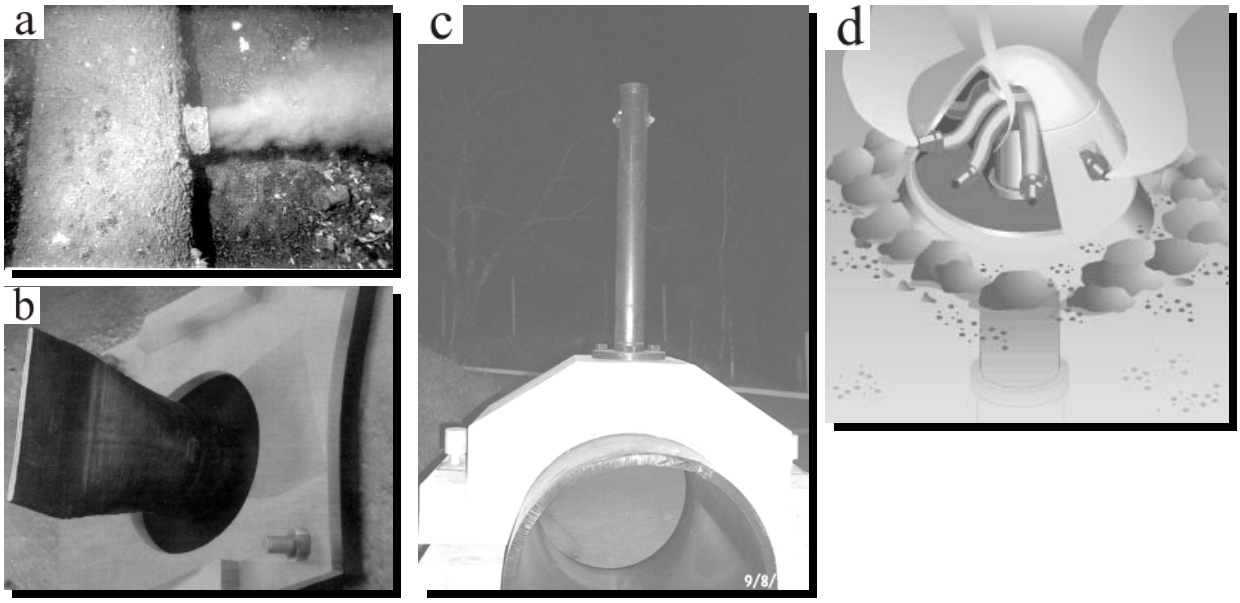


Fig. 3: *a)* simple port (source: Carlo Avanzini), *b)* Variable-area orifices ('duckbill valves', Image: RedValve Company), *c)* riser/port configuration (Guarajá outfall, Sao Paulo State, Brazil), *d)* rosette like port arrangement (Boston Outfall, Image: Massachusetts Water Resources Authority, Boston, USA)

Typical outfalls are several kilometers long and discharge up to 1 m³/s treated effluent through a few ten up to a hundred m long diffuser section with 10 - 50 ports in 10 to 40 meters depth. These constructions may cost a few million Euro (Gunnerson, 1988) and are difficult to construct and maintain due to deep sea diving limits, the strong dependency on weather conditions and the need for uninterrupted discharge for operating systems. Therefore savings in construction and operation are of major importance.

An outfall design must consider both, the hydraulics occurring outside and inside a diffuser. External hydraulics affect the effluent mixing with the ambient fluid, internal hydraulics affect the flow partitioning and related pressure losses in the manifold resulting in a discharge profile along the diffuser. CorHyd covers the internal diffuser hydraulics.

2.2 External hydraulics - dilution requirements

First design steps for the external hydraulics of diffusers are either the usage of simple dilution equations (e.g. Jirka, 2003 or Jirka and Lee 1994) or the direct application of more detailed mixing models (e.g. CORMIX) under given dilution requirements and major choices for the riser/port spacing to find a minimum diffuser length and a first port diameter estimate.

All external hydraulic design methodologies and programs (mixing calculations) are based on properly working diffusers and therefore use homogeneous discharge distributions along the diffuser line as input. Effects of a non-homogeneous discharge distribution can be estimated by simple (conservative) dilution equations for multiport diffusers (Jirka and Lee, 1996), valid for the assumption of a 2-D plume after single jet merging (see Fig. 4). The plume centerline dilution S_c for stagnant water can be obtained with

$$S_c = 0.38\left(\frac{j_0^{1/3} z}{q_0}\right) \qquad (1)$$

where j_0 denotes the buoyancy flux per diffuser length $j_0=g'q_0$, with $g'=\frac{\Delta\rho_e}{\rho_a} g$ and $q_0 = V_jB$, the mass flux per diffuser length with the port exit velocity V_j and the equivalent slot width $B = A_p/l$ (A_p is the port cross section and l the riser spacing, see Fig. 4). z is the observed position in the vertical above the discharging port.

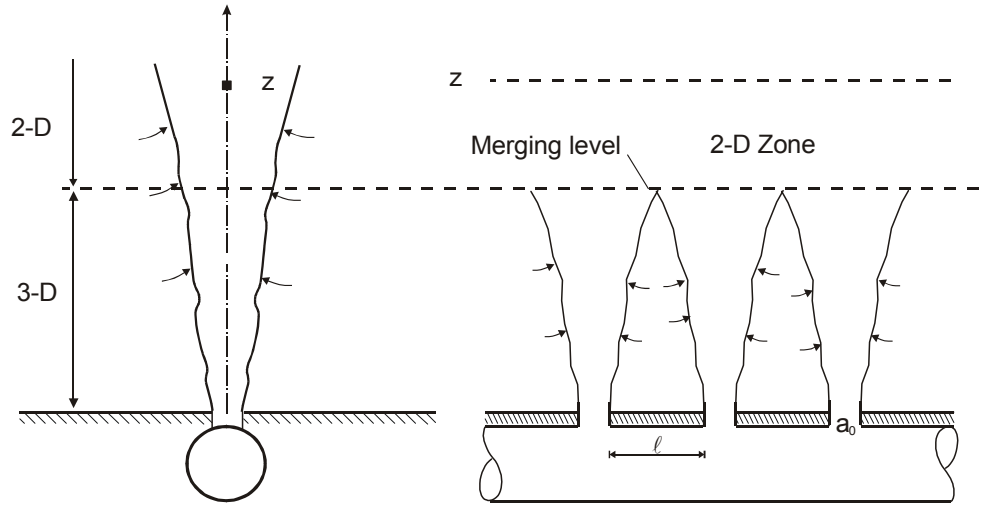


Fig. 4: Definition diagram for plume centerline dilution equation for multiport diffusers

A simple estimate of effects from a distorted discharge profile is a comparison of the centerline dilution for two different mass fluxes:

$$\frac{S_{c1}}{S_{c2}} = \frac{j_{0,1}^{1/3}\, q_{0,2}}{q_{0,1}\, j_{0,2}^{1/3}} = \frac{q_{0,1}^{1/3}\, q_{0,2}}{q_{0,1}\, q_{0,2}^{1/3}} = \left(\frac{q_{0,2}}{q_{0,1}}\right)^{2/3} \qquad (2)$$

A 10% discharge variation $q_{0,2}/q_{0,1} = 0.9$ along a diffuser would therefore, result in dilution difference of 7% ($S_{c1}/S_{c2} = 0{,}93$) along the diffuser line. These differences are often not considered in further mixing calculations and so far could harm the environment or could lead to critical concentrations with respect to the discharge permit.

The combination of CorHyd with CORMIX allows to find an optimized internal hydraulics design (cost effective) resulting in environmental sound solutions.

2.3 Internal hydraulics - operational requirements

CorHyd covers the internal diffuser hydraulics with the following design objectives:

- *uniform discharge distribution along the diffuser* in order to meet dilution requirements and to prevent operational problems (e.g. intrusion of ambient water through ports with low flow). Exceptions should avoid near-shore impacts by keeping the seaward discharge higher.
- *minimized constructional and operational costs* using simple manifold geometries with small losses
- *prevention of off-design operational problems* in order to avoid particle deposition and salt water intrusion during low flow or no-flow periods

- *performance tests against unsteady operations* in order to reach rapidly steady flow condition after purging during start-up, optimize intermittent pumping cycles and consider wave induced circulations and water-hammer

Conflicting design parameters require compromises, which are often not sufficiently resolved (Bleninger et. al, 2004). Existing diffuser programs (Fischer et al., 1979, implemented as code PLUMEHYD; and Wood et al., 1993, implemented as DIFF) have deficiencies for diffuser designs other than pipes with simple ports in the wall. They only consider short risers with negligible friction losses and local losses and lack the implementation of long risers (like in deep-tunneled outfalls) with meaningful frictional and local losses, Y-shaped diffusers, complex port/riser configurations, multiple ports on one riser, duckbill valves or other complex port losses. Design rules regarding the velocity ratios (Fischer et al., 1979) or loss ratios (Weitbrecht et al., 2002) for diffuser sections and downstream ports are only helpful for simple geometries (no changes along the diffuser). For others, they are either unnecessarily conservative or not valid at all, because velocities and losses are changing drastically in actual diffuser installations. Moreover these problems are often not recognized due to poor monitoring conditions in deep sea. Consequences are costly systems in terms of construction, operation and maintenance as well as bad dilution characteristics (Fig. 5).

Fig. 5: Replaced diffuser, which was full of sediment and therefore not working properly (courtesy of Eng. Pedro Campos, Chile)

CorHyd calculates velocities, pressures, head losses and flow rates inside the diffuser pipe and especially at the diffuser port orifices. Planner, designer and operator of outfalls may use it to analyze, predict and monitor the discharge behavior of planned or installed diffusers under different boundary conditions. The combination with CORMIX will provide a direct linkage to subsequent waste plume modeling and mixing zone analysis.

2.4 Manifold processes

Pipe hydraulics are characterized by continuous pressure losses due to wall friction and by local pressure losses due to geometrical changes. Manifold hydraulics (i.e. diffusers) are characterized by several flow separations, where local losses depend not only on geometrical relations but furthermore on the discharge rates. The flow distribution for simple pipe configurations with uniform geometries along the diffuser depends mainly on the ratio of branching losses and manifold losses. But most of the actual diffuser geometries have more complex geometries. Diffusers often discharge fluids with higher or lower density than the receiving waters, which cause an additional buoyant forcing on the fluid flow.

Implemented losses in CorHyd include continuous losses due to friction in all pipes (feeder, diffuser, riser, and port). Local losses are considered automatically in all pipe sections, the feeder pipe, the diffuser manifold and the attached port-riser branches. Furthermore additional local losses may be added manually if necessary:

Local Feeder losses (Fig. 6)

- inlet loss at headworks
- horizontal and vertical bends
- contractions/expansions along the feeder pipe
- flow separation, if several diffusers are mounted on one feeder

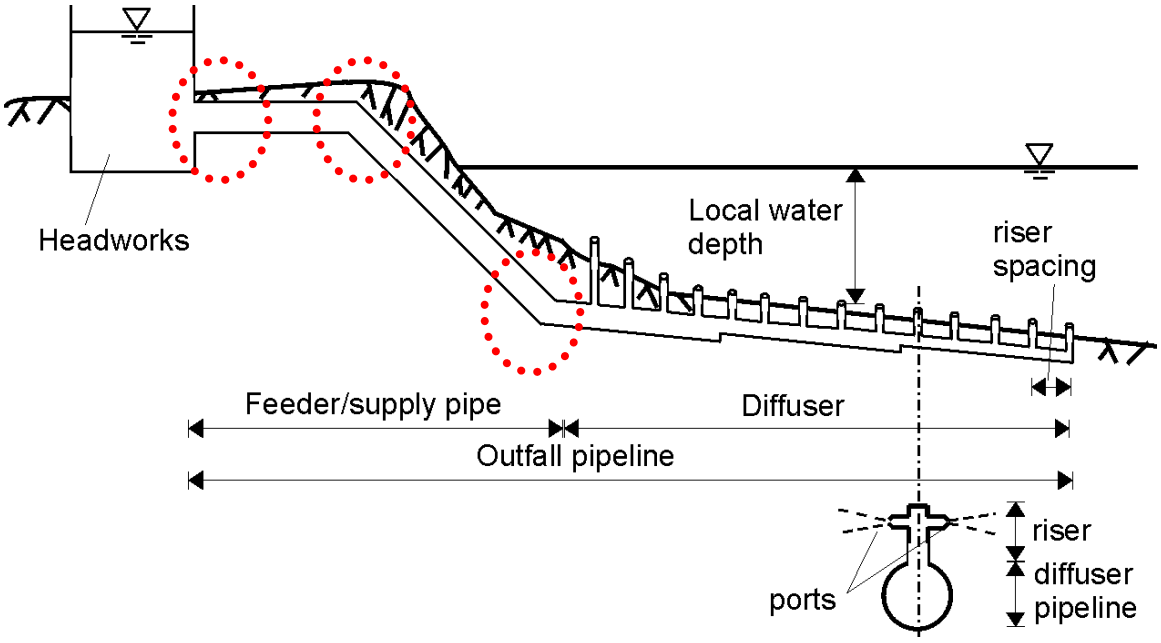


Fig. 6: Local feeder losses

Diffuser manifold losses (Fig. 7)

Implemented local losses along a streamline along the diffuser pipe centerline passing the branch pipes are:

- the division of flow loss for the diffuser pipe passing a riser
- horizontal or vertical bends
- contractions/expansions along the diffuser pipe

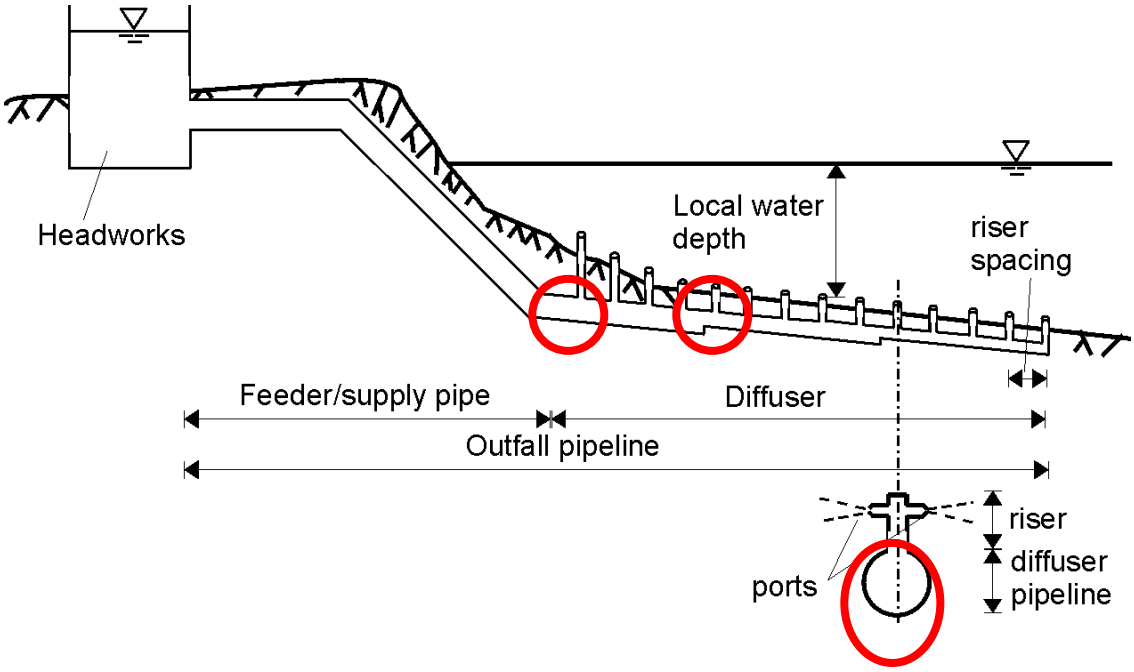


Fig. 7: Local diffuser manifold losses

Port - riser branch losses
Implemented local losses along a streamline going from a diffuser centerline into the riser, then into the port and the discharging jet are:

- the division of flow from the diffuser pipe into a riser
- optional: bends or additional losses in the riser
- the transition or division of flow from riser to port(s)
- optional: additional losses in the port or at the orifice
- optional: contraction of jet
- optional: duckbill valves at the port orifices

Optional means, that either additional known geometry changes or local loss coefficients can manually be added to the generally foreseen local losses in ports and risers. If for example the port is mounted perpendicular onto the riser, this local bending loss is not included but can be added as a known loss. If a riser has more than one port, it is assumed, that the discharge flowing through the riser, is distributed evenly among all ports (i.e. for two ports, both would have half the discharge).

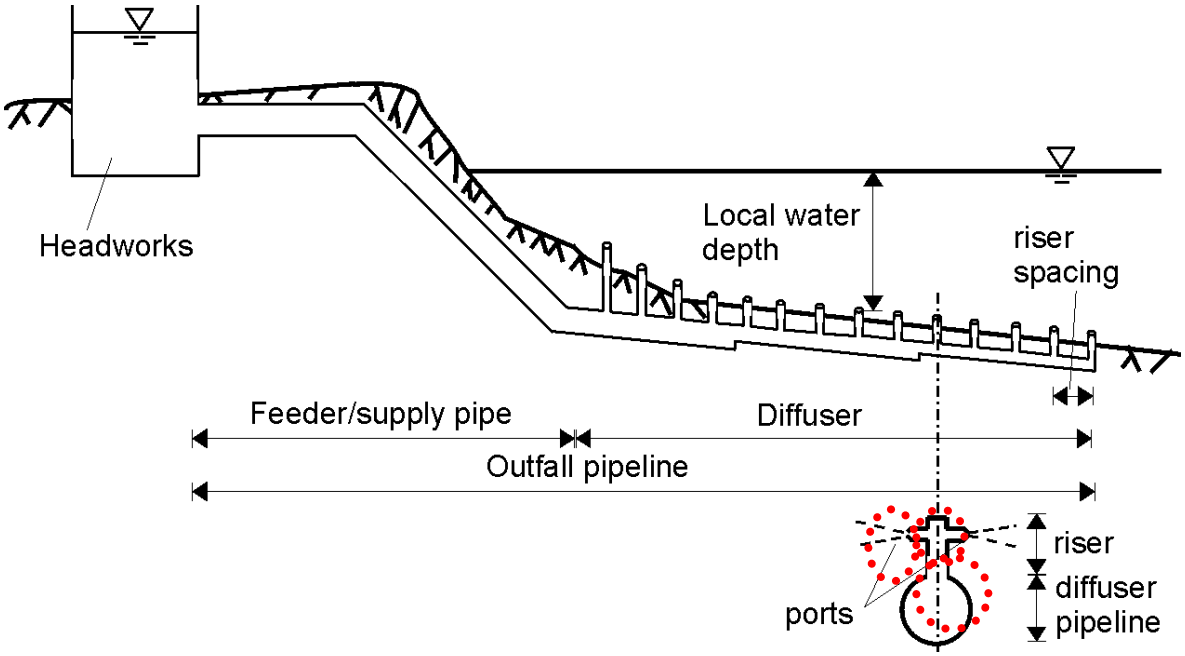


Fig. 8: Local port/riser branch losses

2.4.1 Local loss formulations

Local losses are due to geometrical differences between one cross-sectional area of a pipe and the adjacent one (i.e. expansions, contractions, or bends, Fig. 9) or the inlet or end of a pipe (orifice). These changes may lead to flow detachment processes, reverse currents in deadzones, locally increased accelerations or decelerations, increased turbulence, which all cause energy losses, in closed pipe systems compensated by pressure losses.

Local pressure losses p_l in a pipe system are generally calculated as:

$$p_l = \zeta \cdot \frac{\rho_e \cdot V^2}{2} \quad \text{or as headloss} \quad p_l/\gamma_e = \zeta \cdot \frac{V^2}{2g} \qquad (3)$$

where ζ denotes the dimensionless loss coefficient, ρ_e the effluent density and V the reference velocity either upstream or downstream the geometrical change.

There are numerous publications defining local loss coefficients ζ for a large number of different geometries under different flow conditions. Thus ζ itself may depend on the Reynolds number, the actual flow condition (e.g. flowrate ratios in diverging flows) the distance to previous local losses and geometrical reltions. Comparisons between these publications showed discrepancies even for simple geometries. The choice was in regards to the most accurate works from Idelchik (1986), Miller (1990), and Lee et.al. (1998).

Table 2 gives an overview of implemented local loss coefficients ζ. They are calculated automatically in CorHyd. These assume reasonable high Reynolds numbers (above 10^4) and reasonable geometrical distance between the changes to avoid interaction of losses. Modification of the listed formulations can be found in Idelchik (1986) for special geometries and some limited ranges of Reynolds numbers, although those are not implemented in CorHyd. Furthermore additional optional losses can be added manually for risers and ports. Examples for non-conventional nozzles or flanged orifices are given in the Annex, chapter 10.

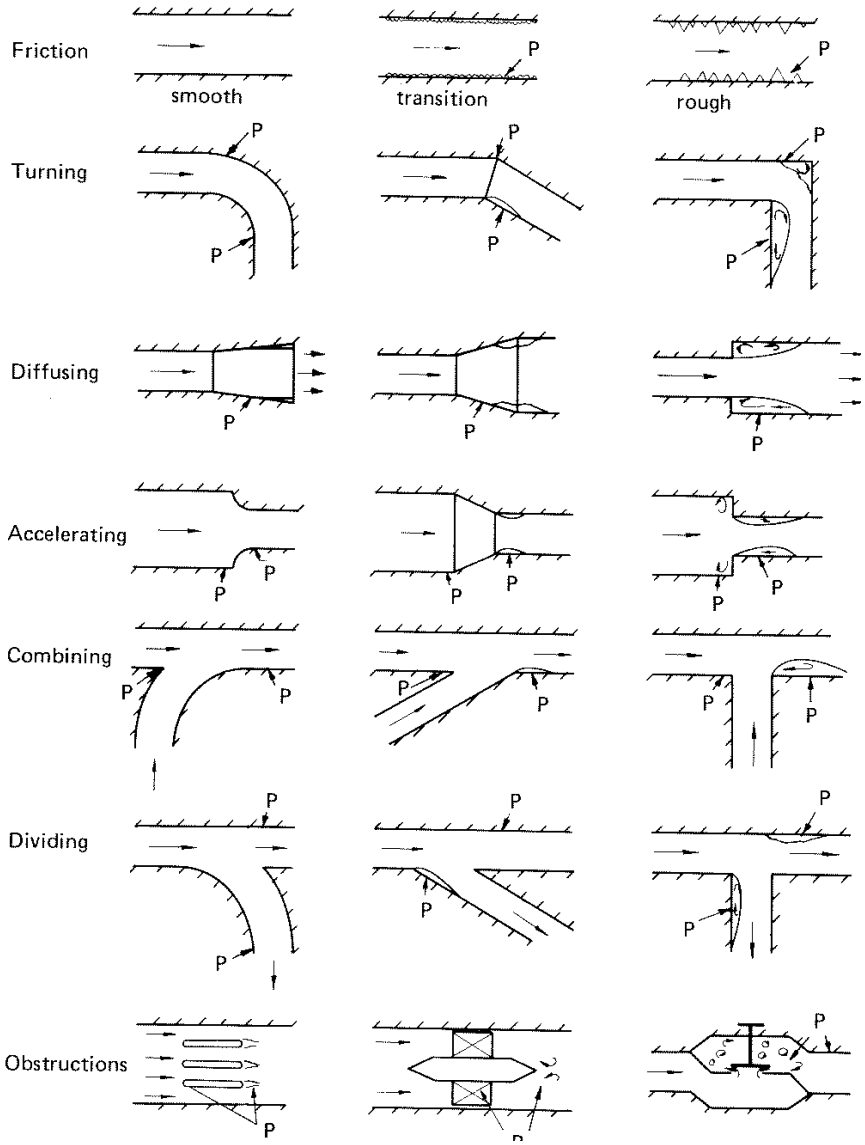
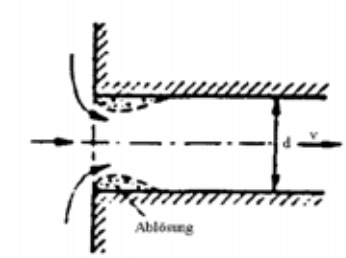
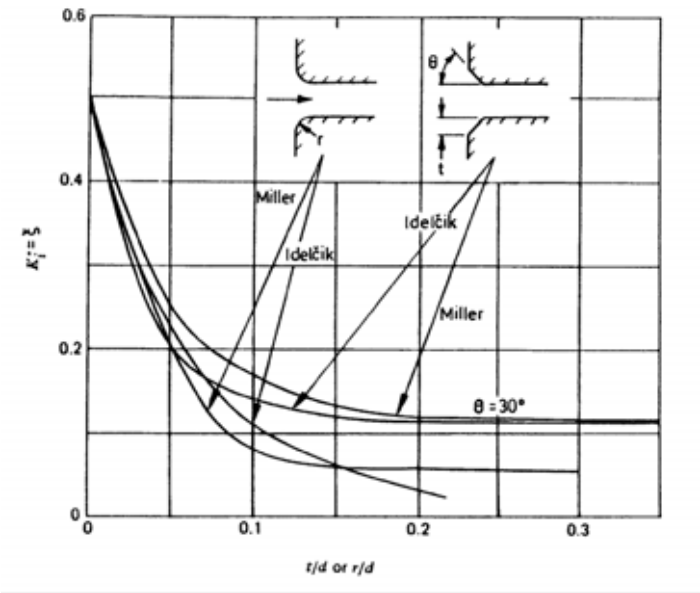
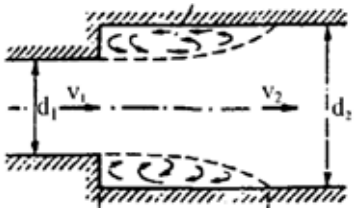
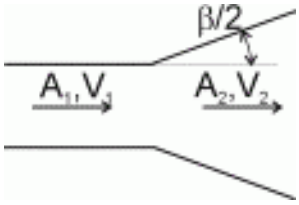
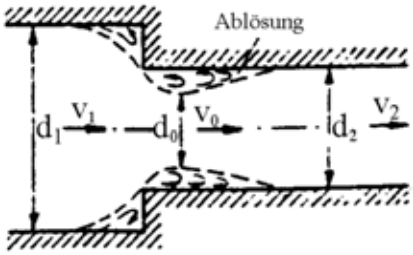
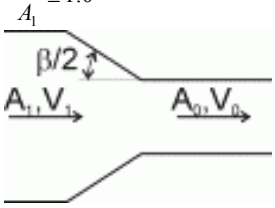


Fig. 9: Examples for local losses in pipe flows (Miller, 1990)

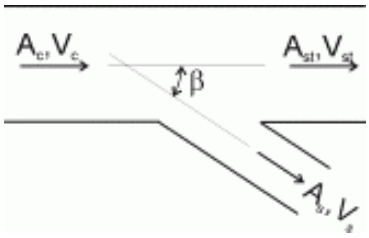
Table 2: Local loss formulations

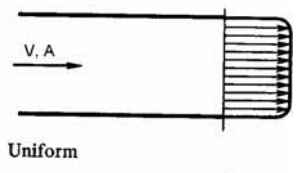
Type of Loss	Definition
Inlet (Reference velocity is V)	**Sharp edged inlet** (Idelchik, 1986) $\zeta = 0.5$  Code (see files: barchart.m, plotlosses.m, report.m, time_series.m, totalHead.m): The value $\zeta = 0.5$ is automatically foreseen in the code, if a feeder pipe exists. The loss is added only after the whole calculation directly in the result files. Although most of the constructions do have sharp edged inlets from the headworks into the feeder pipe other configurations may applied by using the following graphs and changing the code in the mentioned files (zeta_entry = "new value").
	Rounded inlets (Idelchik, 1986, Miller, 1978) 

Expansion (Reference velocity is V_1)	**Sudden expansion** (Idelchik, 1986) $\zeta_e = \left(1 - \frac{A_1}{A_2}\right)^2$  Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m).
	Gradual expansion (Idelchik 1986) $\zeta_e = 3.2 \cdot \tan\frac{\beta}{2} \cdot \sqrt[4]{\tan\frac{\beta}{2}} \left(1 - \frac{A_1}{A_2}\right)^2$ with β in rad  For β > 50°, the formulation for gradual expansion leads to a greater loss coefficient than the one for a sudden expansion. Therefore Idelchiks formulas was adopted so that for β > 50° losses are equal the loss for β = 50°. Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m).
Contraction (Reference velocity is V_2)	**Sudden contraction** (Idelchik, 1986) $\zeta_c = 0.5 \cdot \left(1 - \frac{A_2}{A_1}\right)^{3/4}$  Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m).

	Gradual contraction (Idelchik 1986) $\zeta_c = \left(-0.0125 \cdot n_0^{\,4} + 0.0224 \cdot n_0^{\,3} - 0.00723 \cdot n_0^{\,2} + 0.0044 \cdot n_0 - 0.00745\right) \cdot \left(\beta^3 - 2\pi\beta^2 - 10\beta\right)$ with $n_0 = \frac{A_0}{A_1} \le 1.0$ and β in rad  For β > 50°, the formulation for gradual expansion leads to a greater loss coefficient than the one for a sudden expansion. Therefore Idelchiks formulas was adopted so that for β > 50° losses are equal the loss for β = 50°. Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m).
Bending (reference velocity = velocity after bending	**Bend** (Kalide 1980) $\zeta_0 = \left[0.131 + 0.159\left(\frac{D}{R}\right)^{3.5}\right] \cdot \frac{\delta}{180°}$ where D is the pipe diameter and R the radius of the bend. Often applied as R = 3D. Delta is the angle of the bend (e.g. 90° for rectangular bends). Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m)
	Friction due to bend (Idelchik 1986) $\zeta_{fr} = \lambda \frac{L}{D}$ with $\frac{L}{D} = \pi \frac{\delta}{180°} \frac{R}{D}$

Division of flow	(Idelchik 1986)
	$\zeta_s = \frac{\Delta p_s}{\rho V_s^{\,2}/2} = \frac{\zeta_{c,s}}{\left(V_s/V_c\right)^2}$
	$\zeta_{st} = \frac{\Delta p_{st}}{\rho V_{st}^{\,2}/2} = \frac{\zeta_{c,st}}{\left(V_{st}/V_c\right)^2}$
	$\zeta_{c,s}$ from Diagram 7.15, $\zeta_{c,st}$ from Diagram 7.17 (Idelchik, 1986 or Annex chapter 10). Curves fitted by the following code:
	
	Determination of zeta' (in the following zeta double underline) c,s
	vRatio = (q(i)/Ar(i)) / ((sum_q(i-1)+q(i))/Ad(i));
	if Dr(i)/Dd(i) <= 2/3
	zeta__c_s = 0.7956*vRatio^2 + 0.2732*vRatio + 0.956;
	elseif Dr(i)/Dd(i) == 1
	zeta__c_s = 0.3*vRatio^2 + 1;
	else
	dif = (1-Dr(i)/Dd(i))/(1-2/3);
	zeta__c_s = (0.3*vRatio^2 + 1) ...
	+ dif*((0.7956*vRatio^2 + 0.2732*vRatio + 0.956) - (0.3*vRatio^2 + 1));
	end
	
	Determination of A' from Idelchik Paragraph 15
	aRatio = Ar(i)/Ad(i);
	qRatio = q(i)/(sum_q(i-1)+q(i));
	if aRatio <= 0.35 & qRatio <= 0.4
	Azeta = 1.1 - 0.7*qRatio;

	elseif aRatio <= 0.35 & qRatio > 0.4
	Azeta = 0.85;
	elseif aRatio > 0.35 & qRatio <= 0.6
	Azeta = 1 - 0.65*qRatio;
	else % aRatio > 0.35 & qRatio > 0.6
	Azeta = 0.6;
	end
	zeta_c_s = Azeta * zeta__c_s;
	zeta_s = zeta_c_s / vRatio^2;
	 
	
	Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m):

T-division	(Idelchik 1986) $\zeta_t = 1+1.5(\alpha A_r/A_p)^2$ Code (see files: CommonFeederPipe.m, feederpipes.m, DiffuserLosses.m, Losses_common_feeder.m):
Straight orifice	$\zeta = 1$ 
Side branching orifice	Fischer et al. 1979, for sharp-edged orifices $K_k = 0.63 - 0.58 \cdot \left(V_d^2 / 2gE \right)$ depending on the diffuser centerline velocity V_d and the excess energy head E (see chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**)
Flexible orifices (duckbills)	Lee et.al. (1998) , Red Valve Company, Abromaitis 1995, Elasto-Valve Rubber Products (EVR) $\zeta_{duck} = \frac{H \cdot (\rho_e \cdot g)}{\rho_e \cdot \frac{V_{duck}^2}{2}} = \frac{2 \cdot H \cdot g}{V_{duck}^2}$

Where H denotes the headloss, V_{duck} the discharge velocity which depends on the effective open area A_{duck} which depends on the flow through the valve. All these parameters are dependend also on the used stiffness of the rubber material. The following formulas are taken out of Lee et al. (1998) but should be modified related to the used material from the providing company. If other materials are used the following formulations have to be modified in the code.

Tideflex	H [m]	A_{duck} [cm^2]	V_{duck} [m/s]
TF 100	0,1005 * Q	25,03(1-e^Q/7,988) + 0,309Q	4,103(1-e^Q /4,213) + 0,03825Q
TF 100	0,0634 * Q	13,075 ln Q - 9,201	1,3485 $Q^{0,5536}$
	0,0606 * Q		0,9090 $Q^{0,6089}$
TF 150	0,0232 * Q	38,828 ln Q – 27,300	0,5277 $Q^{0,5558}$
	0,0235 * Q		0,6084 $Q^{0,5638}$
TF 200	0,0124 * Q	40,466 ln Q – 6,429	0,2917 $Q^{0,5967}$
	0,0129 * Q		0,4692 $Q^{0,5395}$
TF 305	0,0067 * Q	95,950 ln Q – 200,940	0,4529 $Q^{0,4732}$
	0,0052 * Q		0,3091 $Q^{0,5203}$

with Q in [l/s]

Code (see files: duckbill.m).

Inaccuracies in pipe siting

$\zeta = n\ \zeta_s$, where n is the number of fittings (ATV-DVWK A110, 2001)

D [mm]	ζ_s
200	0.017
300	0.014
400	0.012
500	0.010
600 - 1000	0.005
> 1000	0

Inaccuracies in pipe fittings

$\zeta = n\ \zeta_f$, where n is the number of fittings (ATV-DVWK A110, 2001)

D [mm]	ζ_f
200	0.009
300	0.006
400	0.004
500	0.003
600 - 1000	0.0015
> 1000	0.001

The overall local loss coefficient for one riser/port configuration is the sum of all applicable coefficients. However, since not all reference velocities are the same the coefficients have to be modified so all losses can be multiplied with the same velocity. For this code, the downstream velocity has been chosen to be the reference velocity V_{ref}. Therefore CorHyd, for example modifies the local loss coefficient due to expansion:

$$\zeta_e = \zeta_{e,orig} \cdot \frac{V_{up}^{\ 2}}{V_{down}^{\ 2}} \qquad (4)$$

with $\zeta_{e,orig}$ being the original expansion coefficient. When multiplying with the square of the downstream velocity V_{down} , it will cancel out and the coefficient will only be multiplied with the reference velocity it is supposed to be multiplied with:

$$\zeta_{e,orig} \cdot \frac{V_{up}^{\ 2}}{V_{down}^{\ 2}} \cdot \frac{\rho_e \cdot V_{down}^{\ 2}}{2} = \zeta_{e,orig} \cdot \frac{\rho_e \cdot V_{up}^{\ 2}}{2} = \zeta_e \cdot \frac{\rho_e \cdot V_{down}^{\ 2}}{2} \qquad (5)$$

A similar modification is implemented for additional entered local losses: If the loss relates to another reference velocity than the one found in the segment described by the given diameter of the Port (D_p), the coefficient is multiplied by the ratio of the two velocities $V_{add}^{\ 2} / V_p^{\ 2}$, where V_{add} is the needed (related) reference velocity for the given local loss coefficient and V_p the velocity due to the given port diameter. However, when entering the loss coefficients, the user usually does not know the discharge through the port and, therefore, does not know the velocity either. But the discharge through one port does not change when reaching a different segment of this port. Therefore, instead of velocities, the modification can be done regarding the flow devided by the areas:

$$\zeta_{add} = \zeta_{add,orig} \cdot \frac{V_{add}^{\ 2}}{V_p^{\ 2}} = \zeta_{add,orig} \cdot \frac{\left(q_i / A_{add}\right)^2}{\left(q_i / A_p\right)^2} = \zeta_{add,orig} \cdot \frac{A_p^{\ 2}}{A_{add}^{\ 2}} \qquad (6)$$

where $\zeta_{add,orig}$ is the original local loss coefficient and A_{add} is the related area. If there are several known additional local losses, each $\zeta_{add,i}$ is determined separately, modified if necessary and then the sum of all losses is entered into the designated space. Using this method, very complicated port-riser configurations can be calculated with the program.

2.4.2 Friction losses

Continuous pressure losses due to friction along the walls or boundary layers in a pipeline are calculated as:

$$p_l = \lambda \cdot \frac{L}{D} \cdot \frac{\rho_e \cdot V^2}{2} \qquad \text{or as headloss } p_l/\gamma_e = \lambda \cdot \frac{L}{D} \cdot \frac{V^2}{2g} \qquad (7)$$

where λ is the friction coefficient, L the length of the considered pipe section, D the diameter, V the velocity in the pipe section, and ρ_e the density of the effluent. For the calculation of the friction coefficient λ, the explicit form described by Swamee and Jain (1976) is used:

$$\lambda = \frac{0.25}{\left[\lg\left(\frac{k_s}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \qquad (8)$$

It is valid for $10^{-6} < \frac{k_s}{D} < 10^{-2}$ and $4 \cdot 10^3 < \mathrm{Re} < 10^5$, where k_s stands for the equivalent sand roughness and the Reynolds number $\mathrm{Re} = VD/\nu_e$, where ν stands for the kinematic viscosity of the effluent.

Values of k_s for different pipe materials and surface conditions of use are listed in Table 3, which is an excerpt of Idelchik (1986). If only Mannings n values are known a conversion to $k_s$can be done by using the formula:

$$k_s = (n\ 5.87\ (2g)^{\wedge 0.5})^6 \qquad (9)$$

Table 3: Equivalent sand roughness for tubes of different materials (Idelchik, 1986)

Table 2-3 Equivalent roughness of tubes and channels

Group	Type of tubes, material	State of tube surface and conditions of use	Δ, mm
		A. Metal tubes	
I	Seamless tubes made from brass, copper, lead	Commercially smooth [122, 129, 139]	0.0015–0.0100
	Aluminum tubes	The same	0.015–0.06
II	Seamless steel tubes (commercial)	1) New, unused (22, 99, 127]	0.02–0.10[a]
		2) Cleaned after many years of use [129]	Up to 0.04
		3) Bituminized [120]	Up to 0.04
		4) Superheated steam pipes of heating systems and water pipes of heating systems with deaeration and chemical treatment of running water [53]	0.10
		5) After one year of use in gas pipelines [22]	0.12
		6) After several years of use as tubing in gas wells under various conditions [4]	0.04–0.20
		7) After several years of use as casings in gas wells under different conditions [4]	0.06–0.22
		8) Saturated steam ducts and water pipes of heating systems with minor water leakage (up to 0.5%) and deaeration of water supplied to balance leakage [53]	0.20
		9) Pipelines of water heating systems independent of the source of supply [13]	0.20
		10) Oil pipelines for intermediate operating conditions [53]	0.20
		11) Moderately corroded [139]	~0.4
		12) Small depositions of scale [139]	~0.4
		13) Steam pipelines operating periodically and condensate pipes with the open system of condensate [53]	0.5
		14) Compressed air pipes from piston- and turbocompressors [53]	0.8
		15) After several years of operation under different conditions (corroded or with small amount of scale) [4, 84, 129]	0.15–1.0

Table 2-3 Equivalent roughness of tubes and channels (*Continued*)

Group	Type of tubes, material	State of tube surface and conditions of use	Δ, mm
		A. Metal tubes (*Cont.*)	
		16) Condensate pipelines operating periodically and water heating pipes with no deaeration and chemical treatment of water and with substantial leakage from the system (up to 1.5–3%) [53]	1.0
		17) Water pipelines previously used [99]	1.2–1.5
		18) With large depositions of scale [129]	~3.0
		19) Poor condition; nonuniform overlapping of joints [119]	⩾5.0
III	Welded steel tubes	1) New or old, but in good condition; welded or riveted joints [122, 139]	0.04–0.10
		2) New, bituminized [128]	~0.05
		3) Used previously, corroded, bitumen partially dissolved [139]	~0.10
		4) Used previously, uniformly corroded [139]	~0.15
		5) Without noticeable unevenness at joints [139]; lacquered on the inside layer (10 mm thick); adequate state of surface [125]	0.3–0.4
		6) Gas mains after many years of use [139]	~0.5
		7) With simple or double transverse riveted joints; lacquered 10 mm thick on the inside or with no lacquer but not corroded [122]	0.6–0.7
		8) Lacquered on the inside but rusted; soiled when transporting water but not corroded [122]	0.95–1.0
		9) Layered deposits; gas mains after 20 years of use [139]	1.1
		10) With double transverse riveted joints, not corroded; soiled during transport of water [99, 139]	1.2–1.5
		11) Small deposits [139]	1.5
		12) With double transverse riveted joints, heavily corroded [122]	2.0
		13) Appreciable deposits [139]	2.0–4.0
		14) Used for 25 years in municipal gas mains, nonuniform deposits of resin and naphthalene [139]	2.4
		15) Poor condition, nonuniform overlapping of joints [122]	⩾5.0
IV	Riveted steel tubes	1) Lateral and longitudinal riveting with one line of rivets; 10 mm thick lacquered on the inside; adequate state of the surface [122]	0.3–0.4
		2) With double longitudinal riveting and simple lateral riveting; 10 mm thick lacquered on the inside, or without lacquer but not corroded [122]	0.6–0.7
		3) With simple lateral and double longitudinal riveting; from 10 to 20 mm thick lacquered or torred on the inside [122]	1.2–1.3
		4) With four to six longitudinal rows of rivets; long period of use [122]	2.0
		5) With four lateral and six longitudinal rows of rivets; joints overlapped on the inside [122]	4.0
		6) Very poor condition; uneven overlapping of joints [122]	⩾5.0
V	Roofing steel sheets	1) Oiled	0.10–0.15
		2) Not oiled	0.02–0.04

Table 2-3 Equivalent roughness of tubes and channels (*Continued*)

Group	Type of tubes, material	State of tube surface and conditions of use	Δ, mm
		A. Metal tubes (*Cont.*)	
VI	Galvanized steel tubes	1) Bright galvanization; new [139]	0.07–0.10
		2) Ordinary galvanization [139]	0.1–0.15
VII	Galvanized sheet steel	1) New [127]	0.15
		2) Used previously [139]	0.1–0.15
VIII	Cast-iron tubes	1) New [114]	0.25–1.0
		2) New, bituminized [139]	0.10–0.15
		3) Asphalt-coated [127]	0.12–0.30
		4) Water pipelines, used previously [99]	1.4
		5) Used previously, corroded [139]	1.0–1.5
		6) With deposits [127, 139]	1.0–1.5
		7) Appreciable deposits [129, 139]	2.0–4.0
		8) Cleaned after use for many years [139]	0.3–1.5
		9) Heavily corroded	Up to 3.0
		B. Concrete, Cement, and Other Tubes and Conduits	
I	Concrete tubes	1) Good surface, plaster finish [139]	0.3–0.8
		2) Average conditions [139]	2.5
		3) Coarse (rough) surface [139]	3–9
II	Reinforced concrete tubes	[84]	2.5
III	Asbestos-cement tubes	1) New [34]	0.05–0.10
		2) Average [84]	~0.60
IV	Cement tubes	1) Smoothed [84]	0.3–0.8
		2) Nonprocessed [84, 129]	1.0–2.0
		3) Mortar at joints not smoothed [122]	1.9–6.4
V	Conduit with a cement-mortar plaster	1) Good plaster made of pure cement with smoothed joints; all asperities removed; metal casing [122]	0.05–0.22
		2) Steel-troweled [84]	0.5
VI	Plaster over a metallic screen	[13]	10–15
VII	Ceramic salt-glazed conduits	[84]	1.4
VIII	Slag-concrete slabs	[13]	1.5
IX	Slag and alabaster-filling slabs	Carefully made slabs [13, 114]	1.0–1.5
		C. Wood, Plywood, and Glass Tubes	
I	Wooden tubes	1) Boards very thoroughly dressed	0.15
		2) Boards well dressed	0.30
		3) Boards undressed but well-fitted	0.70
		4) Boards undressed [139]	1.0
		5) Staved [84]	0.6
II	Plywood tubes	1) Of good-quality birch plywood with transverse grain [1]	0.12
		2) Of good-quality birch plywood with longitudinal grain [1]	0.3–0.05
III	Glass tubes	Pure glass [127]	0.0015–0.010

[a] Depending on how long these were stored.

3 General Features of CorHyd

To allow for an easy input procedure and fast calculations, CorHyd consist of different modules. Depending on the details of the input CorHyd chooses automatically the applicable modules without user interaction. The available modules are

1. One diffuser (simple setup)
2. Y- or T-diffuser (complex Setup with two diffusers), where two diffuser calculations are coupled to be supplied with one feeder pipe only.
3. Both modules 1 and 2 are furthermore subdivided into a module for diffusers without risers or ports (just holes in the wall) and those with risers.
4. All calculations can be done either for a given total discharge and solving for the individual discharges and the total head or for a given total head and solving for the individual discharges and the total discharge.

In each module losses are calculated automatically. The user only has to provide simple geometrical specifications out of those geometrical changes along the pipe are calculated and calculations for loss coefficients are done. An optional input is foreseen, to consider special losses for non-conventional parts.

Three methodologies for the analysis of the internal hydraulics (i.e. flowrate distribution along diffuser) have been adopted by various authors. The first involves a port-to-port analysis (Fischer et al., 1979, Wood et al., 1993) the second discretizes a fictitious porous conduit (French, 1972) while the third is based on solving the governing equations on an Eulerian grid for every point of the diffuser (Shannon, 2002, Mort, 1989). The latter two have the advantage, that unsteady, stratified flow (i.e. saltwater intrusion) calculations are easier to implement than into the port-to-port analysis. But, they have the disadvantage in considering complex geometries and in defining appropriate local loss formulations. Besides numerical grid based calculations are very time consuming.

CorHyd focuses on an optimized design for multiport diffusers for predominant boundary conditions. Slowly varying boundary conditions like diurnal discharge variations, rainfall events or tidal influences are herein considered as quasi steady. Therefore a port-to-port analysis was chosen for CorHyd. CorHyd contains a preprocessor with flexible data input, where all geometries are defined and necessary details can be specified. The postprocessor includes detailed graphical results as well as performance checks for off-design conditions.

3.1 Major Assumptions

3.1.1 Steady flow

CorHyd assumes slowly and uniformly changing boundary parameters.

The assumption of considering mainly steady flow conditions in diffuser hydraulics is based on the following estimates:

For a constant sea water level and a constant water level elevation z_a in the headworks tank and a constant inflow $Q_{in,a}$ a steady flow with velocity V_a and flowrate $Q = Q_{in,a}$ develops in the outfall pipe system (Fig. 10). Now a higher water level $z_b = z_a + \Delta z$ is considered in the headworks tank (e.g. higher inflow $Q_{in,b}$ from treatment plant or additional pumps are switched on). For fast water level rises $\Delta z/\Delta t > 1$ in the headworks, pressure waves including water hammer effects may occur in the pipe system. These should be prevented by operational means and keeping $\Delta z/\Delta t << 1$. After a short time (order of seconds) the pressure waves are dissipated by pipe elasticity and friction and the new pressure difference between headworks z_b and sea water is developed (Fig. 11). But the flow velocity v_a in the whole pipe system still needs time to accelerate to the velocity v_b according to the new pressure difference. This process needs considerable times for outfalls with huge volumes of water in their pipe system. After a time t the flowrate Q will increase to the final flowrate $Q_{in,b.}$ During that time the internal pressure in the outfall is generally higher than for both discharges $Q_{in,a}$ and $Q_{in,b}$ This additional pressure is needed to accelerate the whole fluid to the final velocity (Fig. 12). The energy grade line is more inclined than for cases without acceleration.

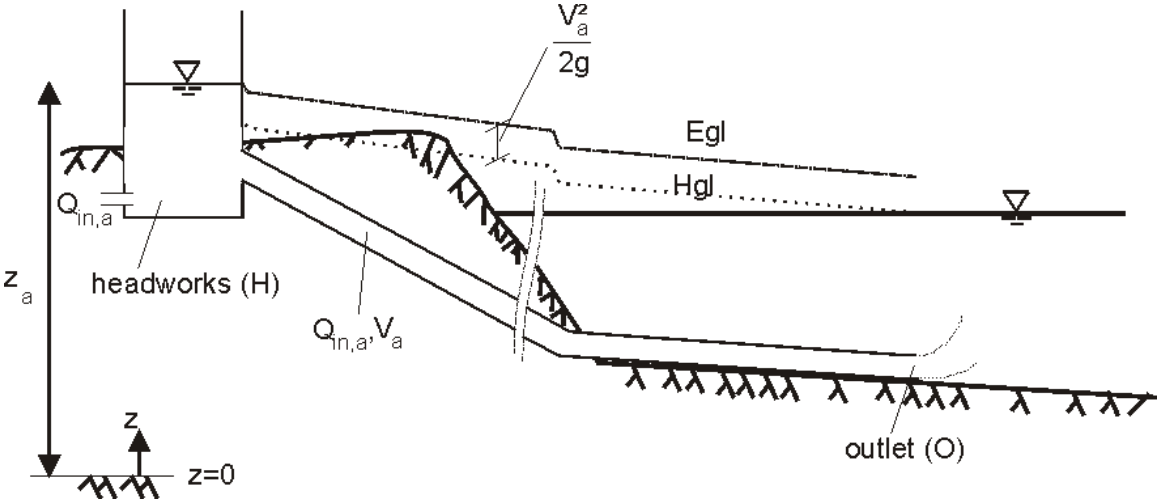


Fig. 10: Steady pipe flow with constant boundary conditions ($Q_{in,a} = Q$)

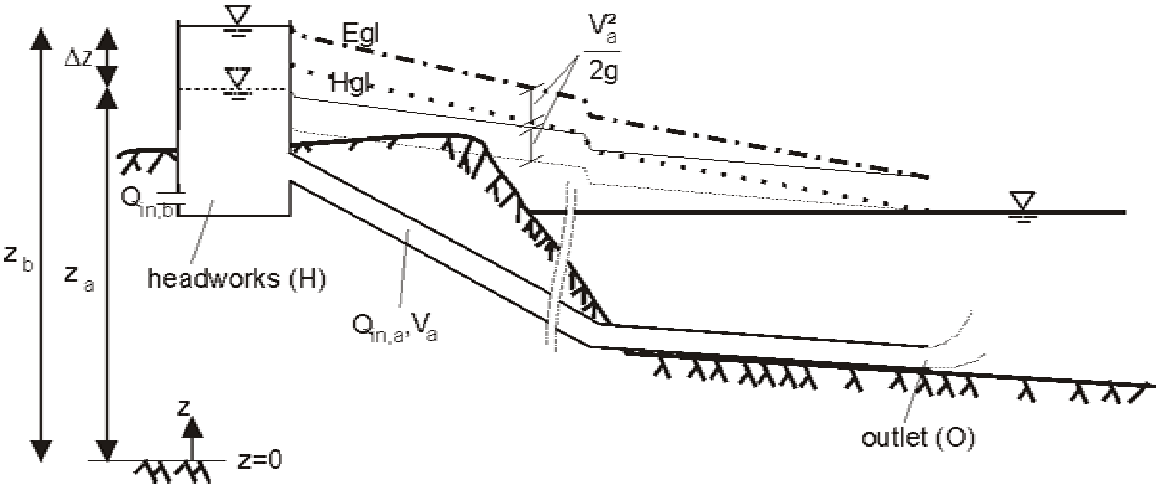


Fig. 11: Pipe flow immediately after a relatively fast change of the water level elevation in the headworks tank ($Q_{in,b} > Q_{in,a}$)

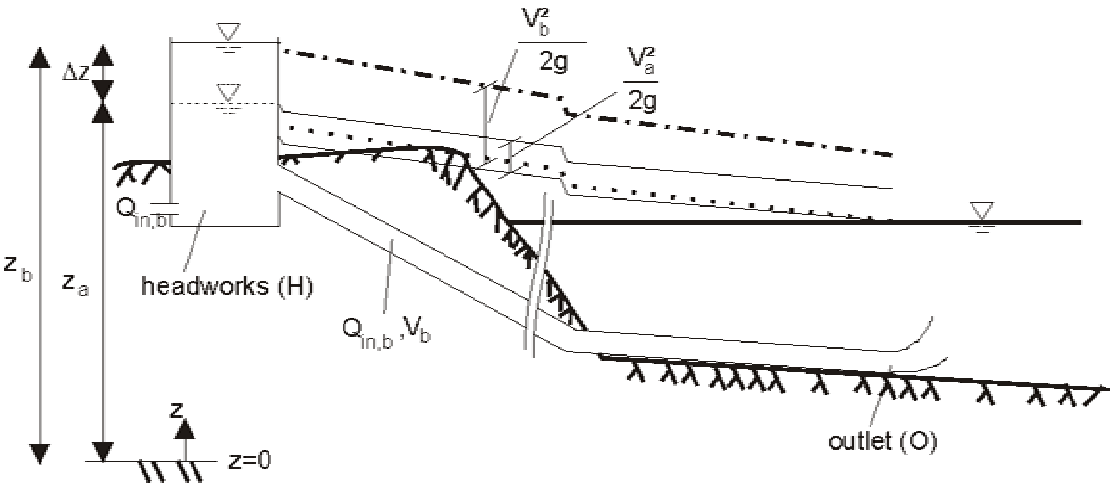


Fig. 12: Pipe flow after the acceleration of the whole fluid in the outfall took place.

To calculate the time t during accelerations take place estimates using momentum and mass conservation equations are analyzed for an *unsteady, incompressible* pipe flow along the coordinate s following a streamline:
The momentum equation is

$$\frac{1}{g}\frac{\partial v}{\partial t}+\frac{\partial E}{\partial s}=0 \qquad (10)$$

where E denotes the energy head.
The mass conservation equation for an incompressible fluid ($\partial\rho/\partial t = 0$) in an non-deformable pipe ($\partial A/\partial t = 0$) is

$$\frac{\partial(\rho v A)}{\partial s}+\frac{\partial(\rho A)}{\partial t}=0 \rightarrow \frac{\partial Q}{\partial s}=0 \;\Leftrightarrow\; v_1(t)A = v_2(t)A = Q(t) \qquad (11)$$

Further assuming a pipeline with constant cross section and length L the first term of (10) is

$$\frac{1}{g}\frac{\partial v}{\partial t}=\frac{1}{g}\frac{dQ}{dt}\int_H^O \frac{1}{A}ds=\frac{1}{g}\frac{dQ}{dt}\frac{L}{A}=\frac{L}{g}\frac{dv}{dt}$$ and the second term is $$\frac{\partial E}{\partial s}=E_O - E_H + \Delta E,$$ where E_H (12)

and E_O (13) denote the energy heads at the water surfaces at the headworks (E_H) and at the outlet (E_O) right after the water level rise in the headworks and before acceleration took place and ΔE the headloss due to friction:

$$E_H=\left(\frac{v_H^2}{2g}+\frac{p_H}{\gamma}+z_H\right)=z_a+\Delta z=z_b \qquad (12)$$

$$E_O=\left(\frac{v^2}{2g}+\frac{p_O}{\gamma}+z_O\right)=\frac{v^2}{2g}+z_{O,a} \qquad (13)$$

$$\Delta E = r\left(\frac{v^2}{2g}\right) \qquad \text{where } r = \lambda L/D \text{ and } \lambda \text{ the friction coefficient} \qquad (14)$$

(12), (13) and (14) in (10) gives

$$\frac{L}{g}\frac{dv}{dt}+\frac{v^2}{2g}+z_{O,a}-z_b+r\left(\frac{v^2}{2g}\right)=0 \qquad (15)$$

Additionally, for the terminal velocity v_b it is

$$z_{O,a}-z_b=-(1+r)\left(\frac{v_b^2}{2g}\right) \qquad (16)$$

(16) solved for r in (15) and assuming a rough regime, where λ is independent of the flow velocity gives

$$\frac{L}{g}\frac{dv}{dt} + \frac{v^2}{2g} + z_{O,a} - z_b - \left(\frac{(z_{O,a} - z_b)2g}{v_b^2} + 1\right)\frac{v^2}{2g}) = 0$$

$$\frac{L}{g}\frac{dv}{dt} + z_{O,a} - z_b - \frac{(z_{O,a} - z_b)v^2}{v_b^2} = 0$$

$$\frac{L}{g}\frac{dv}{dt} + (z_{O,a} - z_b)\left(1 - \frac{v^2}{v_b^2}\right) = 0$$

$$dt = \frac{L}{-g(z_{O,a} - z_b)}\frac{v_b^2}{v_b^2 - v^2}dv$$

$$\int_{t_a}^{t_x} dt = \frac{L}{-g(z_{O,a} - z_b)}\int_{v_a}^{v_x}\frac{v_b^2}{v_b^2 - v^2}dv, \text{ where } v_x = x\ v_b, \text{ when the velocity ratio of the prevailing}$$

velocity v_x and the terminal steady velocity v_b is x.

$$t_x - t_a = \frac{Lv_b}{-g(z_{O,a} - z_b)}\left(\text{arctgh}\left(\frac{v_x}{v_b}\right) - \text{arctgh}\left(\frac{v_a}{v_b}\right)\right)$$

For $t_a = 0$ t_x is the time needed to reach the velocity $v_x = x\ v_b$:

$$t_x = \frac{Lv_b}{-g(z_{O,a} - z_b)}\left(\text{arctgh}\left(\frac{v_x}{v_b}\right) - \text{arctgh}\left(\frac{v_a}{v_b}\right)\right)$$

or using $z_{O,a} - z_b = -(1+r)\left(\frac{v_b^2}{2g}\right)$ it is

$$t_x = \frac{2L}{(1+r)v_b}\left(\text{arctgh}\left(\frac{v_x}{v_b}\right) - \text{arctgh}\left(\frac{v_a}{v_b}\right)\right) \qquad (17)$$

For example applying (17) for x = 0.99 and a 4 km long outfall an acceleration from $v_a = 0.6$ m/s to $v_x = 0.99*1.2$ m/s takes aprox. 2 min. until reaching a velocity of 1 % smaller than the terminal steady flow velocity v_b = 1.2 m/s. Headwork design therefore has to consider storage volumes of discharges, which are causing water level changes increasing/decreasing faster than the fluid in the outfall accelerates. Decreasing discharges furthermore may lead to a situation, where moving fluid in the outfall sucks the effluent from the headworks even beyond the equilibrium level and afterwards swings back and seawater is sucked in the outfall. Latter has critical effects on valves mounted on discharge ports.

CorHyd allows to analyze the internal diffuser hydraulics for steady flow conditions before acceleration or deceleration processes started or after they ended. All unsteady conditions in between during all times t can be analyzed by applying CorHyd with the actual flowrate Q(t) in the pipeline. This is based on the assumption, that the additional pressure in the outfall is not available for changing local parameters (e.g. discharge at one specific port), because inertia of the whole water mass prevents local accelerations or decelerations, which are not directly related to the general flow changes.

Similar considerations can be done for the other boundary, the sea water level, for example due to tidal changes. These will lead to the same results as for changing the available head at the headworks. But high frequent changes like waves, which additionally are local events (wave crest above one riser and wave trough above other) may cause fast pressure changes at the diffuser outlets. This can have effects on the flowrate distribution, if the fluid volume in the riser/port configuration is relatively small (i.e. for holes in the diffuser wall) compared to the additional forcing causing decelerations or accelerations.

Nevertheless the optimization of diffuser geometries - the internal diffuser design - can be made using steady state equations. However very short pumping cycles (order of minutes), full shutdown, purging of a saline wedge during start-up or water-hammer issues cannot be analyzed with this steady state analysis. Unsteady operation (purging during start-up, shutdown of flow or short intermittent pumping cycles, water-hammers) and the related processes like the presence of a saline wedge or the reduction of operating ports will increase pumping costs and effect the flowrate distribution and so far the dilution. Additionally energy costs for purging an intruded outfall are significant. Any unsteady operation should be avoided by using duckbill valves, slowly closing valves or pumps, huge headwork reservoirs allowing long pumping cycles and flushing periods (further storage provision may be necessary when tidal cycles do not allow continuous discharge or gravitational discharge only possible during ebb phase or retention of storm flows necessary to avoid overspill). But if saline intrusion is occurring a saline wedge purging can be guaranteed, for example, by using some velocity criterion (Wilkinson, 1984) or a plug flow system, where one half of the outfall volume is accumulated in the headwork storage and then pumped at high velocities (1.5m/s)(Wood et al. 1993, pp. 122, pp. 326)). The time required to reach steady state once purging was initiated must also be determined (see Wilkinson und Nittim, 1992). Burrows (2001) discovered that if flow at the headworks is interrupted abruptly the effluent flow in the diffuser continues seaward under its own momentum and the dynamic pressure drops rapidly causing the drawing in of seawater from the landward risers. When outfall flow is re-activated the discharge may be prevented from leaving through the landward risers by the inflowing denser sea water and a stable circulation may be established. Furthermore flow accelerations during pump start-up could lead to oscillations (WRC 1990, p. 212). Wave-induced oscillations occur if large waves are passing over a diffuser section in shallow water (Grace, 1978, p. 302). Resonance effects and internal density-induced circulations are possible (Wilkinson, 1985). These have to be analyzed in an additional unsteady analysis, more detailed numerical calculation and/or laboratory experiments.

3.1.2 Single phase pressure pipe

CorHyd assumes the whole pipeline as flowing full under all conditions and especially at the minimum flow rate and minimum tide. It is assumed that air entrance at the inlet is avoided by keeping the top pipe invert under the minimum sea level or using backpressure valves or deaeration chambers.

Stratified flows due to intruded salt water cannot be analyzed in CorHyd.

3.1.3 Geometrical assumptions

CorHyd assumes that the discharge through one specific riser with multiple ports is homogeneously distributed among these ports. This is valid for ports with similar geometry at this diffuser position which are mounted at the same elevation, what is common practice for multiport risers.

CorHyd does apply for multiple ports at one diffuser position, but not for multiple risers at one location on the diffuser pipe.

CorHyd considers round pipes. For rectangular pipes an equivalent diameter has to be used.

The angle between riser and diffuser axis is assumed to be nearly 90°.

3.1.4 Automatic implementation of loss formulations - additional losses

CorHyd automatically applies the necessary local loss formulations for the user given inputs. For special configurations, which need more detailed specifications of geometries additional input is necessary for the calculations.

If for example the port is mounted perpendicular onto the riser, this local bending loss is not included but can be added as a known loss. If a riser has more than one port, it is assumed, that the discharge flowing through the riser with T-shape including this additional loss and is distributed evenly among all ports (i.e. for two ports, both would have half the discharge).

The formulations for local losses applied in CorHyd assume reasonable high Reynolds numbers (above 10^4) and reasonable geometrical distance (above 3 times the diameter) between geometrical changes to avoid interaction of losses. Modifications of the listed formulations can be found in Idelchik (1986) for special geometries and some limited ranges of Reynolds numbers, but have not been implemented in CorHyd.

3.2 Governing Equations

The governing equations are continuity equations at each flow division and the work-energy equation along pipe segments with constant or known flowrate (Fig. 13). Required input data are the **geometry of the discharge structure** with sets of diffuser pipe segment locations x, y, z, riser/port segment geometries (i.e. cross-sections A, riser/port number and allocation, and roughness k_s). Pipe lengths L and pipe joint configurations are calculated automatically out of these parameters. Used indices are 'd' for diffuser pipe sections, 'r' for riser sections, 'p' for port sections and 'j' for jet properties at the vena contracta of the discharging jet. The **ambient** is described by its density ρ_a and the average water level elevation H resulting in different external hydrostatic pressures $p_{a,i}$ at the vertical location of the jet centreline at the vena contracta at each i position along the diffuser pipe, where risers or ports are attached. The **effluent** is described by its fluid density ρ_e and either the total flow rate Q or the total available water level at the headworks (total head H_t).

Additional input fields allow to specify more detailed information on local losses, T- or Y-shaped diffuser configurations or the denomination of clogged or temporary closed ports. Implemented local losses are those from chapter 2.4. Herefore $\zeta_{p,i,j}$, $\zeta_{r,i,j}$, $\zeta_{d,i,j}$ denote the local loss coefficients for each j-component of the total number $n_{p,i}$ of losses in a port, $n_{r,i}$ in a riser or $n_{d,i}$ in the diffuser pipe with pipe cross-sectional areas $A_{p,i,j}$, $A_{r,i,j}$ and $A_{d,i,j}$ respectively. $\lambda_{p,i,j}$, $\lambda_{r,i,j}$ and $\lambda_{d,i,j}$ denote the friction coefficients for related pipe components with length $L_{p,i,j}$, $L_{r,i,j}$ and $L_{d,i,j}$ diameter $D_{p,i,j}$, $D_{r,i,j}$ $D_{d,i,j}$ equivalent pipe roughness $k_{sp,i,j}$, $k_{sr,i,j}$, $k_{sd,i,j}$ respectively for either port, riser or diffuser component j. For each port or riser, the local and friction loss coefficients are determined iteratively, since they depend on the discharge.

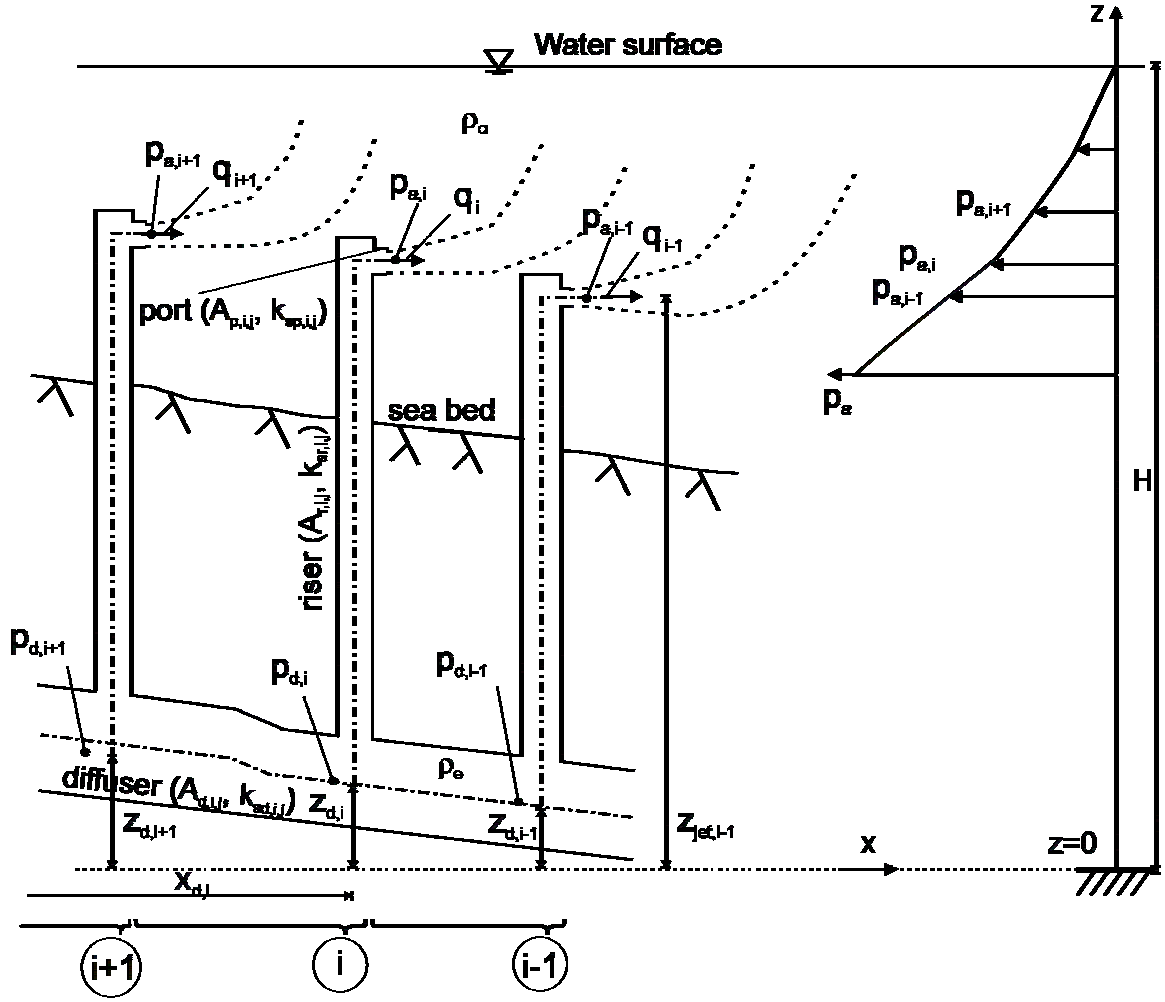


Fig. 13: Definition scheme for the port-to-port analysis: $p_{a,i}$ = ambient pressure, H = average ambient water level elevation, q_i = discharge through one riser/port configuration at elevation $z_{j,i}$. $p_{d,i}$ = internal diffuser pipe pressure upstream a flow division (node) with diffuser pipe centerline elevation $z_{d,i}$ and horizontal pipe location $x_{d,i}$

The discharge q_i at the position i (Fig. 13) is calculated as follows:

1) The **work energy equation** applied along a streamline **following the diffuser pipe** centerline results in eq. (18). It equals the diffuser pressure $p_{d,i}$ directly upstream the port/riser branch with the known downstream diffuser pressure $p_{d,i-1}$ plus the known static pressure difference due to the elevation difference, plus the dynamic pressure difference plus the known losses occurring in the main diffuser pipe. The losses are divided into friction losses and local losses like bends and diameter changes or the passage of a branch opening.

$$p_{d,i} = p_{d,i-1} + \rho_e g\left(z_{d,i-1} - z_{d,i}\right) + \frac{\rho_e}{2A_{d,i-1}^{\,2}}\left(\sum_{k=1}^{i-1} q_k\right)^2 - \frac{\rho_e}{2A_{d,i}^{2}}\left(\sum_{k=1}^{i} q_k\right)^2 + \text{Losses}_{d,i}$$

$$\text{Losses}_{d,i} = \frac{\rho_e}{2}\left(\sum_{k=1}^{i-1} q_k\right)^2 \left[\sum_{j=1}^{n_{d,i-1}} \frac{1}{A_{d,i-1,j}^{\,2}}\left(\zeta_{d,i-1,j} + \lambda_{d,i-1,j}\frac{L_{d,i-1,j}}{D_{d,i-1,j}}\right)\right] \qquad (18)$$

2) The **work energy equation** applied along a streamline **following the branch pipe** and leaving the diffuser through the orifice results in eq. (19). It equals the upstream diffuser pressure $p_{d,i}$ with the ambient pressure $p_{a,i}$ plus the static pressure difference due to the

elevation difference between diffuser centerline and jet centerline, plus dynamic pressure difference between the diffuser and one single jet plus the losses occurring in all pipe segments between these points.

$$p_{d,i} = p_{a,i} + \rho_e g(z_{jet,i} - z_{d,i}) + \frac{\rho_e}{2(C_{c,i}A_{p,i})^2}(\alpha_i q_i)^2 - \frac{\rho_e}{2A_{d,i}^2}\left(\sum_{k=1}^{i} q_k\right)^2 + Losses_i$$

$$Losses_i = \frac{\rho_e q_i^2}{2}\left[\sum_{j=1}^{n_{p,i}}\left(\frac{\alpha_i}{A_{p,i,j}}\right)^2\left(\zeta_{p,i,j} + \frac{\lambda_{p,i,j}L_{p,i,j}}{D_{p,i,j}}\right) + \sum_{j=1}^{n_{r,i}}\left(\frac{1}{A_{r,i,j}}\right)^2\left(\zeta_{r,i,j} + \frac{\lambda_{r,i,j}L_{r,i,j}}{D_{r,i,j}}\right)\right] \quad (19)$$

$C_{c,i}$ denotes the jet contraction coefficient either given by the user or calculated iteratively if Duckbill Valves are applied $C_{c,i,DBV} = \alpha_i q_i / (V_{DBV,i} A_{p,i})$ with $V_{DBV,i}$ = duckbill jet velocity dependent on discharge. If multiple ports are applied a single jet discharge is $q_{jet,i} = \alpha_i q_i$ with α_i = 1/(number of ports at a riser at position i).

Solving eq. (18) = (19) for an individual discharge q_i gives

$$q_i = \sqrt{\frac{\frac{2}{\rho_e}(p_{d,i-1} - p_{a,i}) + 2g(z_{d,i-1} - z_{jet,i}) + \left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2} + \sum_{j=1}^{n_{d,i-1}}\frac{1}{A_{d,i-1,j}^2}\left(\zeta_{d,i-1,j} + \lambda_{d,i-1,j}\frac{L_{d,i-1,j}}{D_{d,i-1,j}}\right)\right]}{\frac{\alpha_i^2}{(C_{c,i}A_{p,i})^2} + \sum_{j=1}^{n_{p,i}}\left(\frac{\alpha_i}{A_{p,i,j}}\right)^2\left(\zeta_{p,i,j} + \frac{\lambda_{p,i,j}L_{p,i,j}}{D_{p,i,j}}\right) + \sum_{j=1}^{n_{r,i}}\left(\frac{1}{A_{r,i,j}}\right)^2\left(\zeta_{r,i,j} + \frac{\lambda_{r,i,j}L_{r,i,j}}{D_{r,i,j}}\right)}} \quad (20)$$

For simple diffusers equation (20) reduces to equation (21) if no risers and no port configurations are applied and the diffuser is just represented by simple holes in the pipe wall. Equation (21) is the one presented in Fischer et al., 1979 which has been used for simple diffuser calculations.

$$q_i = C_{c,i}A_{p,i}\sqrt{\frac{2}{\rho_e}(p_{d,i-1} - p_{a,i}) + \left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2} + \sum_{j=1}^{n_{d,i-1}}\frac{1}{A_{d,i-1,j}^2}\left(\zeta_{d,i-1,j} + \lambda_{d,i-1,j}\frac{L_{d,i-1,j}}{D_{d,i-1,j}}\right)\right]} \quad (21)$$

Fischer et al. (1979) defined a loss coefficient $C_{c,i}$ for sharp-edged entrances:

$$C_{c,i} = 0.63 - \frac{0.58}{2g}\left(\left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2}\right]\left(\frac{2}{\rho_e}(p_{d,i-1} - p_{a,i}) + \left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2}\right]\right)^{-1}\right)$$

and for bell-mouthed ports:

$$C_{c,i} = 0.975\left(1 - \frac{1}{2g}\left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2}\right]\left(\frac{2}{\rho_e}(p_{d,i-1} - p_{a,i}) + \left(\sum_{k=1}^{i-1} q_k\right)^2\left[\frac{1}{A_{d,i-1}^2}\right]\right)^{-1}\right)^{3/8}$$

CorHyd furthermore allows to apply Duckbill valves also on simple diffuser systems and therefore uses the previously defined additional local loss formulations, which are additionally integrated in the calculations of the coefficient C_c.

3.3 Solving scheme

The governing equation can be solved either for a given head or a given total discharge. For both a first estimate is used as a starting value and further iterations lead to the final value.

3.3.1 Solving for total head

At the first port/riser on the seaward side (i = 1) an initial discharge q_1 is estimated, for example $q_1 = Q/N$ with Q = total discharge and N = total number of risers. Equation (19) then allows to calculate the first internal pressure of the diffuser $p_{d,1}$. The further discharges q_2 until q_N are calculated using equation (20). A final application of equation (18) allows to calculate $p_{d,N+1}$, the necessary pressure at the headworks to drive the system. The total head H_t can be calculated by $H_t = p_{d,N+1}/\gamma_{effluent}$ if the water level elevation of a gravity driven system has to be defined. The calculated total discharge is $Q_c = \sum_{k=1}^{N} q_k$. The difference to the planned total discharge is $diff_c = Q - Q_c$. If necessary (i.e. for $diff_c > Q/10000$) CorHyd performes further iterations with modified estimates $q_{1,c}$.

To achieve faster convergence the following algorithm (eq. (22)) has been implemented to calculate $q_{1,c}$:

$$q_{1,1} = Q/N;\ \ q_{1,2} = q_{1,1}\sqrt{\frac{Q}{Q_1}};\ q_{1,c} = q_{1,c-2}diff_{c-1} - q_{1,c-1}\frac{diff_{c-2}}{diff_{c-1} - diff_{c-2}} \text{ for } (c>2) \qquad (22)$$

The iteration stops if the difference between the given total discharge and the calculated total discharge is less than $10^{-5}Q$. The results are individual port/riser discharges and velocities in all pipe sections along the diffuser and a total head. These can be displayed or printed with further output options.

3.3.2 Solving for total flow

At the first port/riser on the seaward side (i = 1) an initial internal pressure $p_{d,1}$ is estimated, for example $p_{d,1} = H_t\,\gamma_e/N + p_{a,1} + \gamma_e(z_{jet,i} - z_{d,i})$ with H_t = total head at headworks. Equation (19) then allows to calculate the first discharge q_1. The further discharges q_2 until q_N are calculated using equation (20). A final application of equation (18) allows to calculate $p_{d,N+1}$, the necessary pressure at the headworks to drive the system. The total head H_t can be calculated by $H_t = p_{d,N+1}/\gamma_e$ if the water level of a gravity driven system has to be defined. The calculated total discharge is $Q_c = \sum_{k=1}^{N} q_k$. The difference to the planned total head is $diff_c = H_t - H_{tc}$. If necessary (i.e. for $diff_c > H_t/10000$) CorHyd performes further iterations with modified estimates $p_{d,1,c}$.

To achieve faster convergence the following algorithm has been implemented to calculate $p_{d,1,c}$:

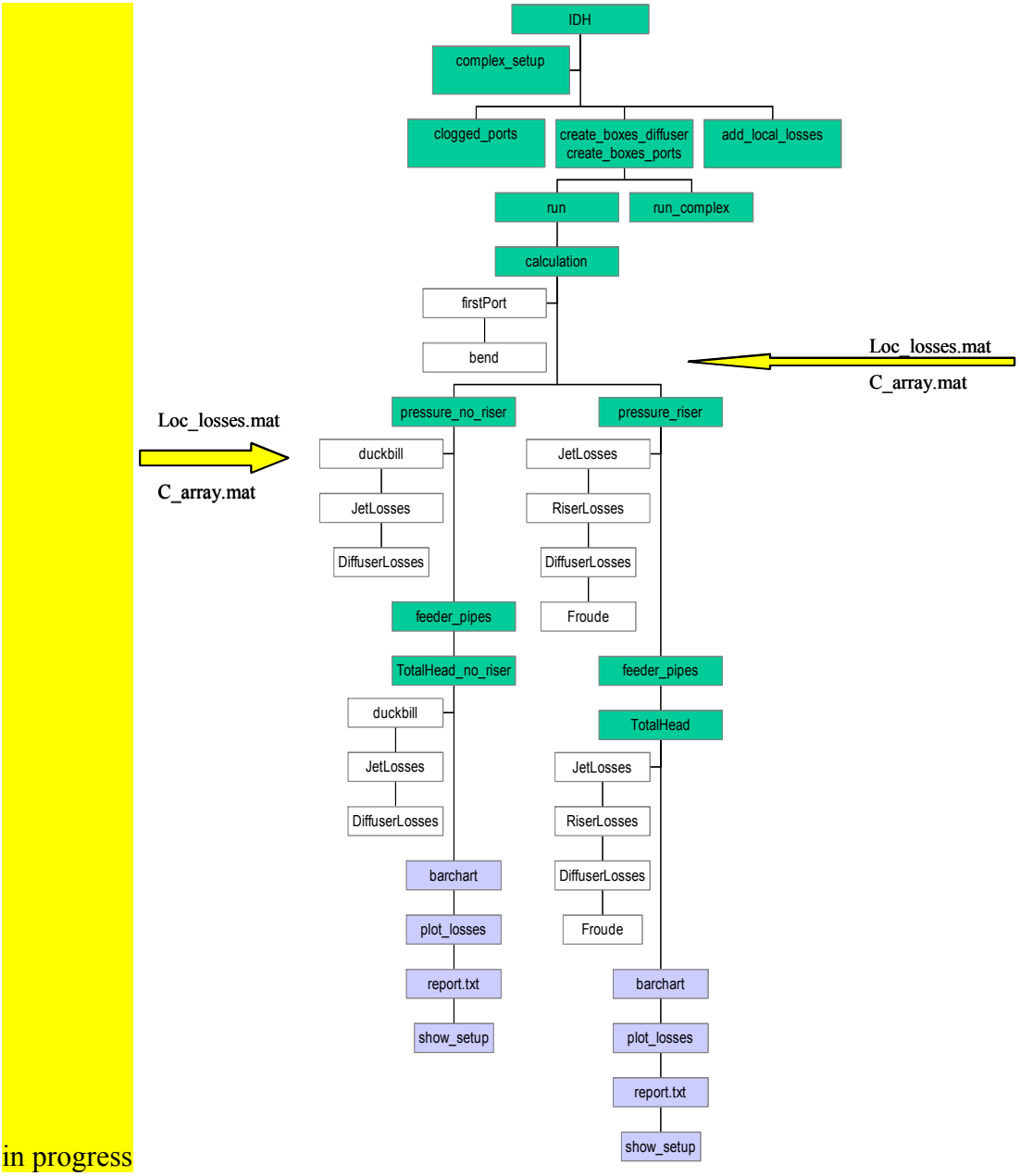
$$p_{d,1,1} = H_t\gamma_e/N + p_{a,1} + \gamma_e(z_{jet,i} - z_{d,i});\ \ p_{d,1,2} = p_{d,1,1}\sqrt{\frac{H_t}{H_{t1}}};\ p_{d,1,c} = p_{d,1,c-2}diff_{c-1} - p_{d,1,c-1}\frac{diff_{c-2}}{diff_{c-1} - diff_{c-2}}$$

for (c>2) (23)

The iteration stops if the difference between the given total head and the calculated total head is less than $10^{-5}H_t$. The results are individual port/riser discharges and velocities in all pipe sections along the diffuser and a total discharge. These can be displayed or printed with further output options.

3.4 System processing sequence and structure of simulation elements

For easier understanding of the code as well as to reduce the number of repeated lines, the program consists of several short subprograms. The main program that reads in the data and calls the subprograms for calculations is called IDH (Internal Diffuser Hydraulics). For easy input and clarity purposes, the program has a graphical user interface (GUI). Fig. 14 shows the processing sequence and structure of the code elements, which are furthermore explained in detail in Table 4. There is a first division in single and multiple diffusers, than a second division in diffuser with and without riser and a third division depending on the parameter to solve for (total head or total discharge and individual discharges).



in progress

Fig. 14: CorHyd organigram for the algorithm

Table 4: CorHyd subroutines and their purpose

in progress, still to be finished

1. Simple Setup, one diffuser only

add_local_losses.m	GUI for additional local losses (if the user likes to put more losses on a port or riser than the ones applied in the code)	input
barchart.m	prints the results into a bar chart	output
bend.m	calculates the angles of pipe bends having the node locations (x,y,z)	function
calculations.m	calculates diameters and areas, length and slope of the diffuser/feeder Section, the static external heads outside of the ports from input data	input and some preparatory calculations
check_length.m	checks if the input is possible	input check
choose system	GUI	input
clearVar.m	clears all variables	function
clogged_ports.m	checks and sorts the ports which the user marked to be clogged. These ports have no discharge in the calculation and should not be considered	function
commonData.m	reads in common data and starts calculations.m	input
commonfeederpipe.m	calculates velocities and losses in the feeder pipe (no ports or risers attached)	function
create_boxes_diffuser.m	creates additional input boxes for the complex system	input
create_boxes_ports.m	creates additional input boxes for the complex system	input
darcy.m	calculates λ the friction coefficient	function
deviation_Thead.m	calculates the deviation of the total head for the system	output function
diffuserlosses.m	calculates the loss coefficients ζ for the diffuser	function
duckbill.m	calculates losses ζ for duckbill valves	function
feeder_pipes.m	calculates the pressure along the feeder pipe	general function
firstport.m	calculates the coordinates of first port of group and starts riser_location.m	function
firstuncloggedport.m	locates the clogged ports and puts zero discharge on them	function
Froude.m	calculates the port densimetric Froude number, necessary for further diffuser analysis, like purging	function
idh.m	main program	start
idh_txt.m	main program without GUI but with txt input	start txt
jetlosses.m	calculates the loss coefficients ζ for the ports	function
lastcommon.m	calculates parameter at last common coordinate	function
local_losses.m	calculates and summarizes the local losses	function
losses.m	GUI for additional local losses	input
losses_common_feeder.m	calculates the pressure in common feeder pipes	function
plot_losses.m	plots the energy grade line and the hydraulic grade line	output
pressure_riser.m	main function for calculating the pressures and discharges along the diffuser	main function
readvariables.m	reads in the variables	input
report.m	creates the text output file	output
riser_location.m	calculates the locations of the riser using the x,y,z input of the nodes	
riserlosses.m	calculates the losses ζ in a riser	function
run.m	starts the different calculations	start after GUI
sedimentation.m	calculates a criteria for start of sedimentation in the diffuser	function
show_setup.m	displays the diffuser setup in a graph	output
totalhead.m	calculates the maximum total discharge for a given maximum total head	starts the iteration with given total

		head instead of discharge

NO Riser system

pressure_no_riser.m	main function for calculating the pressures and discharges along the diffuser	main function
totalhead_norisers.m	calculates the maximum total discharge for a given maximum total head	starts the iteration with given total head instead of discharge

Complex System (two diffuser)

bendComplex1.m	calculates the angles of pipe bends having the node locations (x,y,z)	function
bendComplex2.m	calculates the angles of pipe bends having the node locations (x,y,z)	function
calcComplex.m	program calculation for complex systems	input and some preparatory calculations
complex2.m	GUI for the complex system	input
complex_losses.m	calculates the loss coefficient at the junction of two or more diffusers on one feeder (still a dummy value)	function
compsys.m	M-file for GUI of the complex system	input
conversion1.m	converts variables for the comples system	function
conversion2.m	converts variables for the complex system	function
conversion_back1.m	converts variables for the complex system	function
conversion_back2.m	converts variables for the complex system	function
create_boxes_complex.m	creates additional input boxes for the complex system	input
create_boxes_complex_port.m	creates additional input boxes for the complex system	input
display_complex.m	plots the results (bar charts)	output
display_energy_complex.m	plots the energy grade line and the hydraulic grade line	output
display_setup_complex.m	plots the geometry of the complex system	output
feeder_pipes_complex.m	calculates the pressure along the feeder pipe	general function
firstportcomplex1.m	calculates the coordinates of first port of group and starts riser_locationcomplex1.m	
firstportcomplex2.m	calculates the coordinates of first port of group and starts riser_locationcomplex2.m	
local_lossescomplex1.m	calculates and summarizes the local losses	function
local_lossescomplex2.m	calculates and summarizes the local losses	function
pressure_riser.m	main function for calculating the pressures and discharges along the diffuser	main function
report_complex.m	creates the text output file	output
riser_locationcomplex1.m	calculates the locations of the riser using the x,y,z input of the nodes	function
riser_locationcomplex2.m	calculates the locations of the riser using the x,y,z input of the nodes	function
runcomplex.m	starts the different calculations	start after GUI

NO Riser complex system

pressure_no_risercomplex.m	main function for calculating the pressures and discharges along the diffuser	main function

4 Data Input

Input can either be done by typing the data directly into the designated spaces or by importing an existing text file (Menu: File | Load File). Input can be saved into a ASCII file (Menu: File | Save File). Additional inputs (e.g. Y-diffuser or further losses) may be defined in sub windows, by typing in the data.

Fig. 15 illustrates the used Cartesian coordinate system, which origin is user defined. It is recommended to use a fixed datum for vertical coordinates, and to locate the x-coordinate close to parallel to the diffuser line for better visualization of the results.

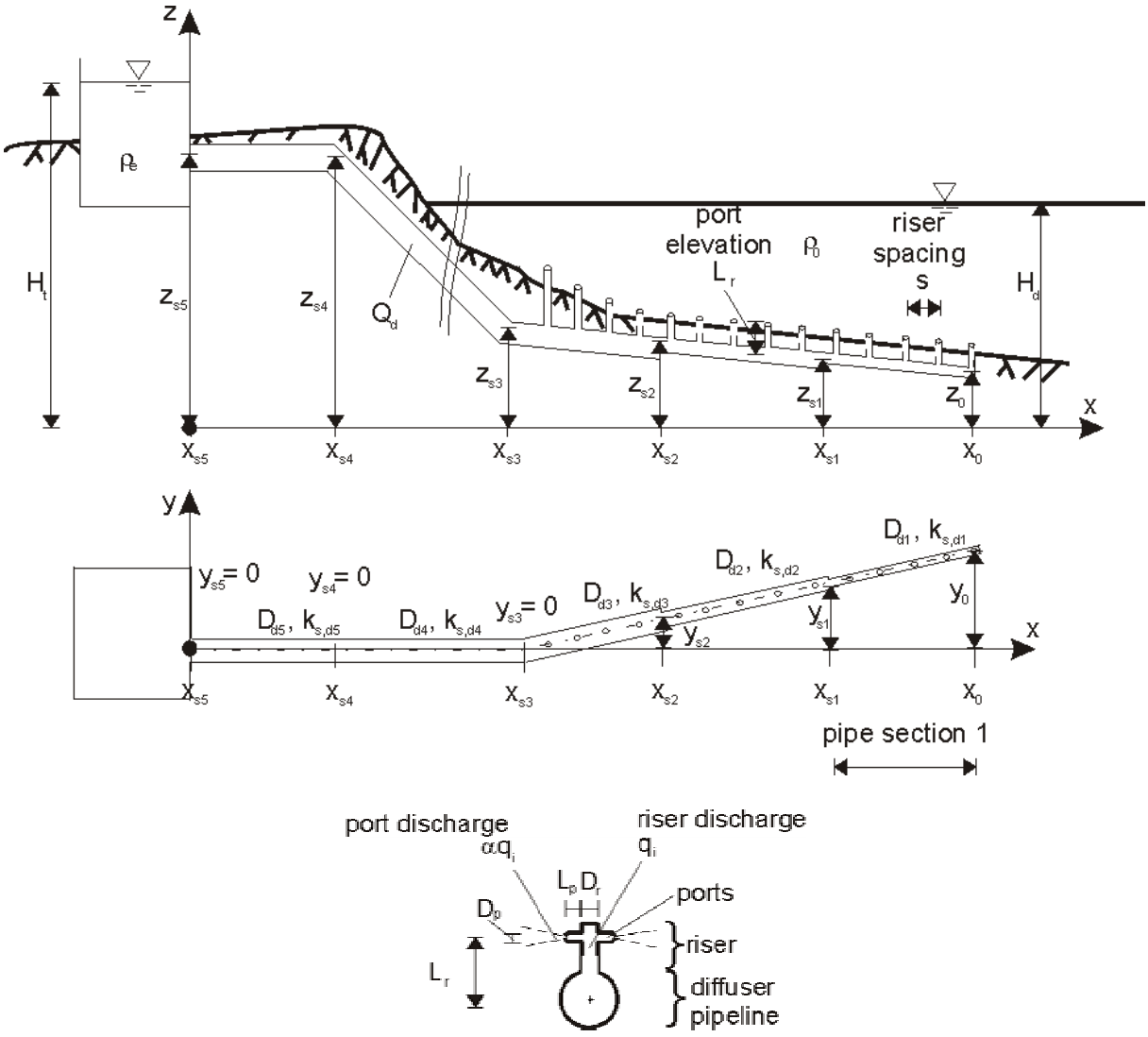


Fig. 15: Coordinate system used in CorHyd. Five pipe sections and two port/riser groups are shown in this example.

Before hitting the *Run* button, the user can choose the format of the output by checking the appropriate radio buttons in the upper right hand corner. Possible outputs include a diagram showing the selected configuration, a text file, a graph showing the energy and pressure grade lines, and a bar chart showing the riser discharges, diffuser velocities just upstream of every riser and the port velocities. When the *Run* button is hit, the data is read into variables and passed on to subprograms responsible for computation of discharges and pressures.

Fig. 16 shows the GUI with an example input. The graphical user interface consists of 5 tabs: Ambient Data (i.e. parameters describing the ambient water body), Effluent Data, Diffuser/Feeder Pipe Configurations (i.e. location, roughness, diameter, etc. of the main pipe; here, 6 different sections are chosen), Port/Riser Configurations (i.e. location, roughness, diameters etc. of the different risers and ports; here, 5 different port-riser groups are chosen), and Output (i.e. Text File, energy line, discharges, and the setup of the outfall). Since none of the port-riser groups is located in segment 6 of the main pipe, this is, by definition, a feeder. It should be noticed that two ports per riser were chosen for riser groups 1 and 2. As output, the energy line (*EL, PL, WL*) and the bar chart showing discharges and velocities (*Discharge (Bar chart)*) were selected.

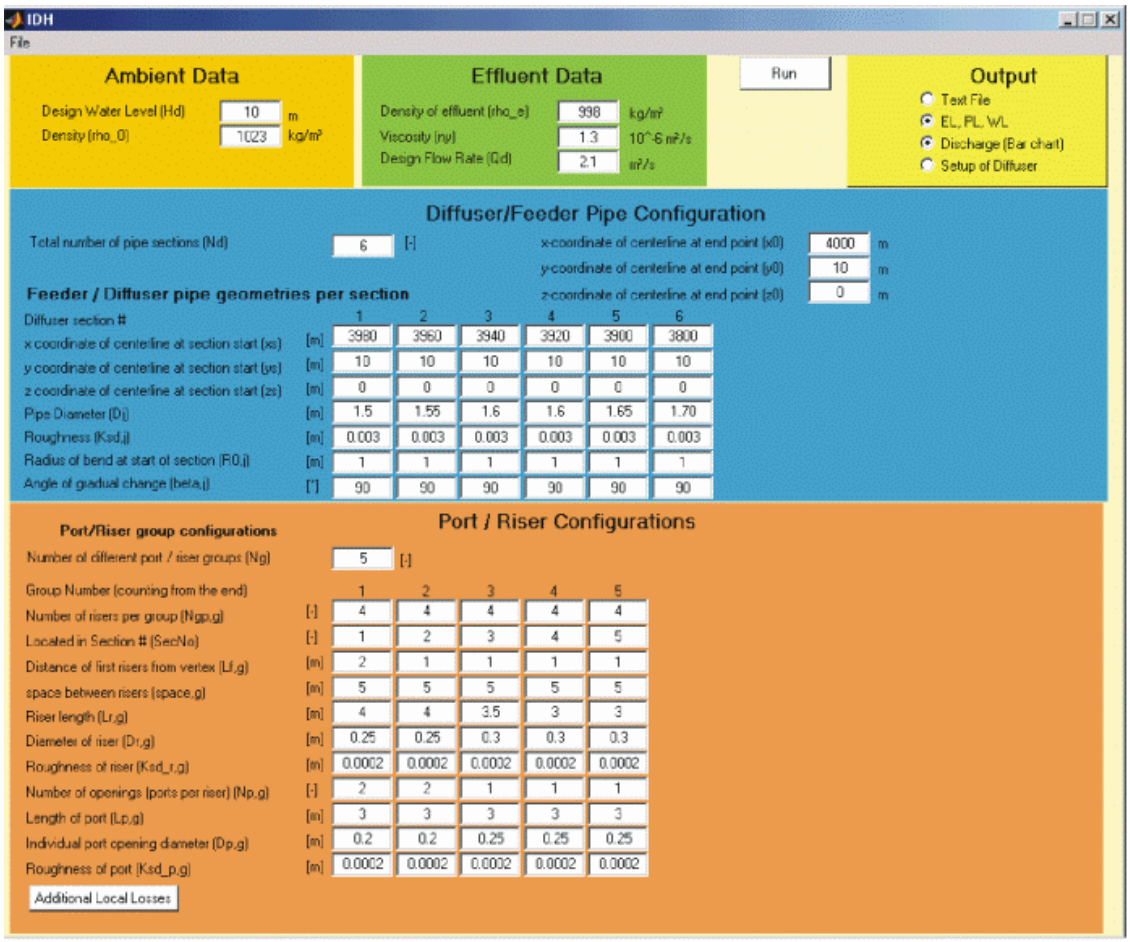

IDH
File
Ambient Data
Design Water Level (Hd) 10 m
Density (rho_0) 1023 kg/m³
Effluent Data
Density of effluent (rho_e) 998 kg/m³
Viscosity (ny) 1.3 10^-6 m²/s
Design Flow Rate (Qd) 2.1 m³/s
Run
Output
Text File
EL, PL, WL
Discharge (Bar chart)
Setup of Diffuser
Diffuser/Feeder Pipe Configuration
Total number of pipe sections (Nd) 6 [-]
x-coordinate of centerline at end point (x0) 4000 m
y-coordinate of centerline at end point (y0) 10 m
z-coordinate of centerline at end point (z0) 0 m
Feeder / Diffuser pipe geometries per section
Diffuser section # 1 2 3 4 5 6
x coordinate of centerline at section start (xs) [m] 3980 3960 3940 3920 3900 3800
y coordinate of centerline at section start (ys) [m] 10 10 10 10 10 10
z coordinate of centerline at section start (zs) [m] 0 0 0 0 0 0
Pipe Diameter (Di) [m] 1.5 1.55 1.6 1.6 1.65 1.70
Roughness (Ksd,i) [m] 0.003 0.003 0.003 0.003 0.003 0.003
Radius of bend at start of section (R0,i) [m] 1 1 1 1 1 1
Angle of gradual change (beta,i) [°] 90 90 90 90 90 90
Port/Riser group configurations
Port / Riser Configurations
Number of different port / riser groups (Ng) 5 [-]
Group Number (counting from the end) 1 2 3 4 5
Number of risers per group (Ngp,g) [-] 4 4 4 4 4
Located in Section # (SecNo) [-] 1 2 3 4 5
Distance of first risers from vertex (Lf,g) [m] 2 1 1 1 1
space between risers (space,g) [m] 5 5 5 5 5
Riser length (Lr,g) [m] 4 4 3.5 3 3
Diameter of riser (Dr,g) [m] 0.25 0.25 0.3 0.3 0.3
Roughness of riser (Ksd_r,g) [m] 0.0002 0.0002 0.0002 0.0002 0.0002
Number of openings (ports per riser) (Np,g) [-] 2 2 1 1 1
Length of port (Lp,g) [m] 3 3 3 3 3
Individual port opening diameter (Dp,g) [m] 0.2 0.2 0.25 0.25 0.25
Roughness of port (Ksd_p,g) [m] 0.0002 0.0002 0.0002 0.0002 0.0002
Additional Local Losses

Fig. 16: The graphical user interface of CorHyd

The following chapters explain the data input for each parameter and furthermore recommend which design values should be used. The design philosophy is based on the idea that the diffuser should operate with maximum flow and highest ambient water level elevation with further performance tests for intermediate operational schemes.

4.1 Ambient Data

The first calculation should be done using the average water level elevation at discharge location as value for the ambient water level elevation H_d . Furthermore the average ambient density ρ_0 should be specified. Performance checks should explicitly done for the case of maximum average water level elevation ($H_{max} > H_d$) and maximum average ambient density

($\rho_{0,max} > \rho_0$). Further sensitivity analysis or time-series runs (chapter 6.2) allow for more detailed analysis of diffuser performance for changing ambient boundary conditions, like tidal water level changes or seasonal density variations. Typical values for sea-water density are ρ_0 = 1021-1026 kg/m³

4.2 Effluent Data

The design flow rate Q_d shall be the maximum foreseen at the end of design life. Generally there is a headwork basin (or the treatment plant itself) with sufficient capacity to accept daily peaks and storm waters (or an additional storm water outfall) resulting in an average flow rate for the outfall. In this case the design can be made on the average daily maximum flow at life end. If there is no or a too small basin (the ratio of the peak rate of flow to the average rate of flow might range from 6 for small areas down to 1.5 for larger areas) and just a storm water overflow the design flowrate is the daily peak flow excluding storm waters. If there is nothing foreseen for daily peaks and storm waters the design discharge has to be the maximum daily flowrate including stormwater discharges. The latter design discharge does not occur on a daily basis, therefore optimization procedures for non-design discharges are even more important than for the other cases.

Performance checks should explicitly done for the foreseen near future scenarios often considering increasing flows in 5, 10 or 20 years. Further sensitivity analysis or time-series runs (chapter 6.2) allow for more detailed analysis of diffuser performance for changing ambient boundary conditions.

Instead of solving for the total head H_t of a given design flow Q_d CorHyd also allows to solve for the flow rate for a given total head in the headworks. Headwork buildings or treatment plant pumps are often limited and the outfall has to be designed for a maximum total head in the headworks.

Effluent density ρ_e and viscosity ν generally do not change significantly. Often used values for municipal waste water is ρ_e = 996-998 kg/m³ and $\nu = 1.31 \ 10^{-6}$ m²/s (ATV-DVWK A110, 2001).

4.3 Feeder and diffuser

The main outfall pipe consist of the feeder pipe, which conveys the effluent to the discharge location and the diffuser pipe, which disperses the effluent in the ambient. The input of both, feeder and diffuser pipe sections is done via the start and end point coordinates x_s, y_s, z_s, the diameter D_d and the roughness $k_{s,d}$. To reduce the input parameters the pipeline is schematized with pipe sections. The number of used sections is N_d. Section limits are locations where either bends or diameter changes or roughness changes occur. Fig. 15 shows the coordinate system for the parameter input related to the coordinates of section fittings. The fittings itself can be characterized by the radius R (typical R = $3D_d$) of a bend if bends between sections occur or an angle β (typical 90 - 180°) for gradual diameter changes are applied (see 2.4.1 for details). The user should try to define as less sections as possible, but as much as necessary to represent the general position of the pipeline. The sections can be chosen independently of the port/riser configurations.

The feeder diameter design is constraint by a maximum diameter to allow scouring of sediments during low flow periods. The near future design discharge Q_{nf} (daily maximum)

should therefore result in feeder velocities $v_{f,nf} > 0.5$ m/s (DIN EN 1671, ATV-DVWK-A 110 (2001) and ATV-DVWK-A 116 (2005)). This corresponds to a maximum feeder pipe diameter of $D_{d,max} = (Q_{nf}8/\pi)^{0.5} \approx 1{,}6\, Q_{nf}^{0.5}$. The feeder velocity for the far future design flowrate Q_{ff} and the same diameter results then in $v_{f,ff} = v_{f,nf}Q_{ff}/Q_{nf}$. Generally flowrates do not more than double or triple during the lifetime of an outfall, so far field feeder velocities are from 1 to 2 m/s, what is clearly acceptable in terms of operational viewpoints considering the related energy losses.

As the feeder also the diffuser pipe is constraint by a maximum scouring diameter. Theoretically this would result in a diffuser with different pipe segments as much as risers, and, under the assumption of a homogeneous discharge distribution, each with a maximal diameter of $D_{d,max,i} = (8Q_{nf}i/(N\pi))^{0.5}$, where N denotes the total number of risers and i the observed pipe section before the i-th riser starting counting offshore. Although best for sediment removal this solution, also called tapering generally is too expensive to install (about 20 % more expansive than single diameter diffuser) and maintain (i.e. cleaning). Besides the continuous tapering after one or more branches the only alternative is decreasing the diffuser diameter as a whole. Thus a simple configuration is achieved, although increased friction losses and separation losses in the diffuser pipe will increase the total head. Changes of the diffuser diameter cause only moderate changes in the discharge profile. If tapering is applied the changes in the discharge profile are even smaller than in the case of changing the diameter generally.

By applying different diameters for CorHyd calculations it has to be considered, that pipes are not available in all sizes and only diameters are applied which are given as internal diameters in catalogues of pipe producers.

4.4 Port / Riser configurations

Instead of typing in ports or risers one by one the concept of port/riser groups was used (Delft Hydraulics, 1995) for easy and fast data input. The user should try to use as less groups as possible but as much as necessary to achieve optimized design.

The total number of different groups is N_g. For each port/riser group the number of used risers N_{gp} and the location on the diffuser pipe section has to be given. E.g. group number one consist of $N_{gp} = 15$ risers each of them with the same specific port/riser configuration and is mounted along the pipe section number one. Details of the parameter definitions are visualized in Fig. 15. The next input denotes the spacing L_g between each group and the spacing S between each riser in one group (often both are the same). It follows the input of the port elevation L_r above the diffuser centerline (necessary for calculating the external pressure at the outlets). If no risers are applied the value should be zero. It follows the input for the port and riser diameters D_r, D_p and the roughness $k_{s,r}$. If no risers are applied riser diameter and roughness should be zero. If more than one port is located at one position or at one riser the number of ports N_p has to be given. If ports consist of little attached pipes their length L_p and related roughness $k_{s,p}$ should be given.

A 50 mm minimum port size for secondary- or tertiary-level treated effluent and storm water inflow to the sewage system was suggested by Wilkinson and Wareham (1996) for avoiding the risk of blockage. Furthermore a minimum port size of 70 to 100 mm for primary treatment plants (just screening and settling tank). The maximum port diameter should generally be smaller than the diffuser pipeline diameter D_d at upstream position to achieve higher discharge velocities and avoid saltwater intrusion during low flows. The riser diameter D_r

should allow for riser velocities, which are bigger than the diffuser velocities, but smaller than the port velocities to allow for a constant flow acceleration.

For design discharges a homogeneous distribution should be achieved and often only gravity discharge should allow to drive the system. This can be done by either changing port diameters along the diffuser or applying variable area orifices. In comparison with fixed (constant or invariable) port diameters the effective open area of variable area orifices (duckbill valves) changes with different discharges. Therefore, they are good for non or low discharge scenarios, where intrusion has to be prevented. Decreasing fixed port diameter leads to a more homogeneous discharge distribution but to increased losses and total head due to higher velocities. Attached duckbill valves give almost homogeneous discharge profiles, due to the discharge dependent open area.

By applying different diameters for CorHyd calculations it has to be considered, that pipes are not available in all sizes and only diameters are applied which are given as internal diameters in catalogues of pipe producers. Nevertheless often a few centimeters difference in the port orifice diameter makes considerable differences if applied all along the diffuser or in designated pipe sections. Furthermore changes of port diameters might be necessary during lifetime of the diffuser to adopt for changing boundary conditions. Both can easily realized by flanges at the diffuser itself or by flanges at the riser pipe an attached port pipe, if risers are necessary. A tap with a hole of an intermediate size can then be fixed on these flanges and easily replaced even as submarine work. Attention has to be paid to avoid abrupt diameter changes and sharp edges to reduce the additional losses caused by these constructional details.

4.5 Additional local losses (sub-menu)

If complex geometries are applied, which are not automatically foreseen in the CorHyd loss formulations, further loss values may be included for ports or risers. Fig. 17 shows the pop-up window, which opens after clicking on additional local losses. In this window additional loss coefficients ζ (related to the port velocity) can be given as well as jet contraction ratios C_c. Furthermore it is possible to define here, if Duckbill valves are applied and which nominal diameter they have. Also further studies can be done by introducing additional losses and analyzing their effects to check the system-performance-sensitivity on loss formulations and so far the necessity in doing laboratory studies for achieving more accurate loss formulations. For risers additional local losses (related to the riser velocity) as well as additional bends or a total riser length can be given to achieve more accurate results, if complex geometries are applied.

For example flanges with taps fixed on a port pipe cause an additional loss and a contracting jet. Both effects can be considered and evaluated by entering the loss coefficient (e.g. from chapter 10.2 in the annex) and the contraction coefficient.

The data given in the sub-window is not saved with the overall result and has to be put again after the calculation.

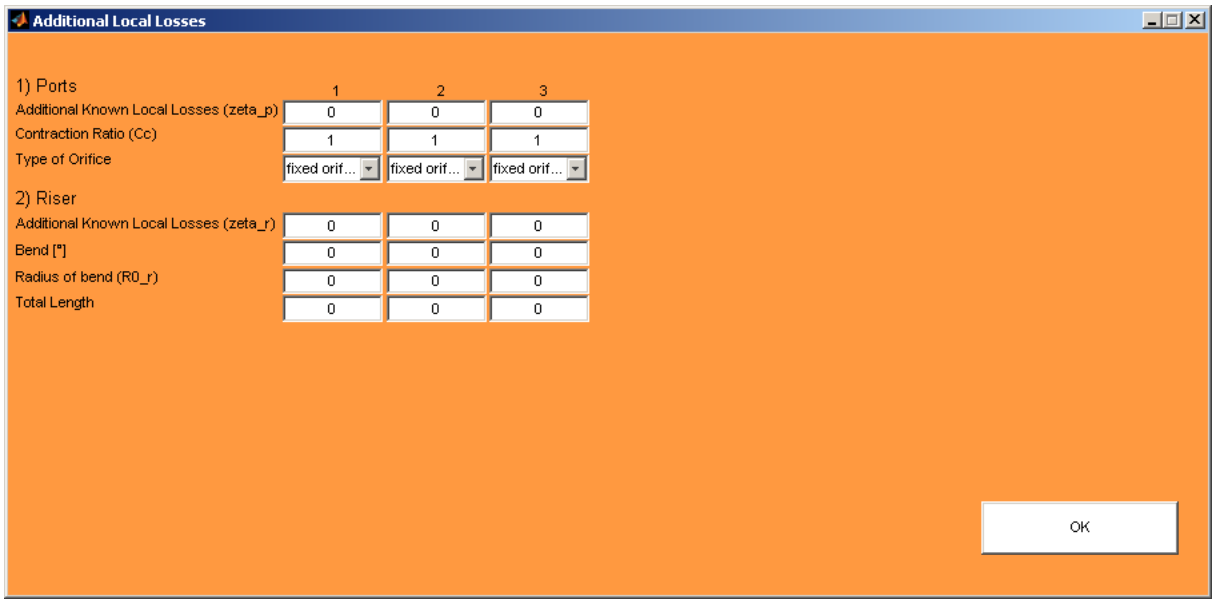


Fig. 17: Pop-up window for further input of local losses at ports or risers

4.6 Blocked ports (sub-menu)

If the user knows blocked ports for already operating diffusers, these can be considered in the calculation to analyze this modified diffuser system. This may also be done for analyzing diffusers with temporarily closed ports in early design periods. Fig. 18 shows the input window for clogged ports, where only the number of the ports has to be put.

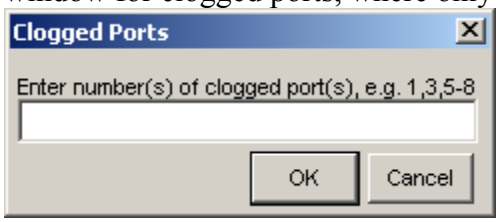


Fig. 18: Pop-up window for clogged ports input.

4.7 Y or T-diffuser (sub-menus)

If two diffuser are connected to one riser the program allows to calculate each diffuser separately and iterate to meet the joined boundary condition (equal pressure) at the end of the feeder pipe. The input for each diffuser is analogue to the input for single diffuser outfalls. Fig. 19 shows the input window for the first and Fig. 20 the input window of the second diffuser of the two diffusers. Each diffuser can be saved separately in a file.

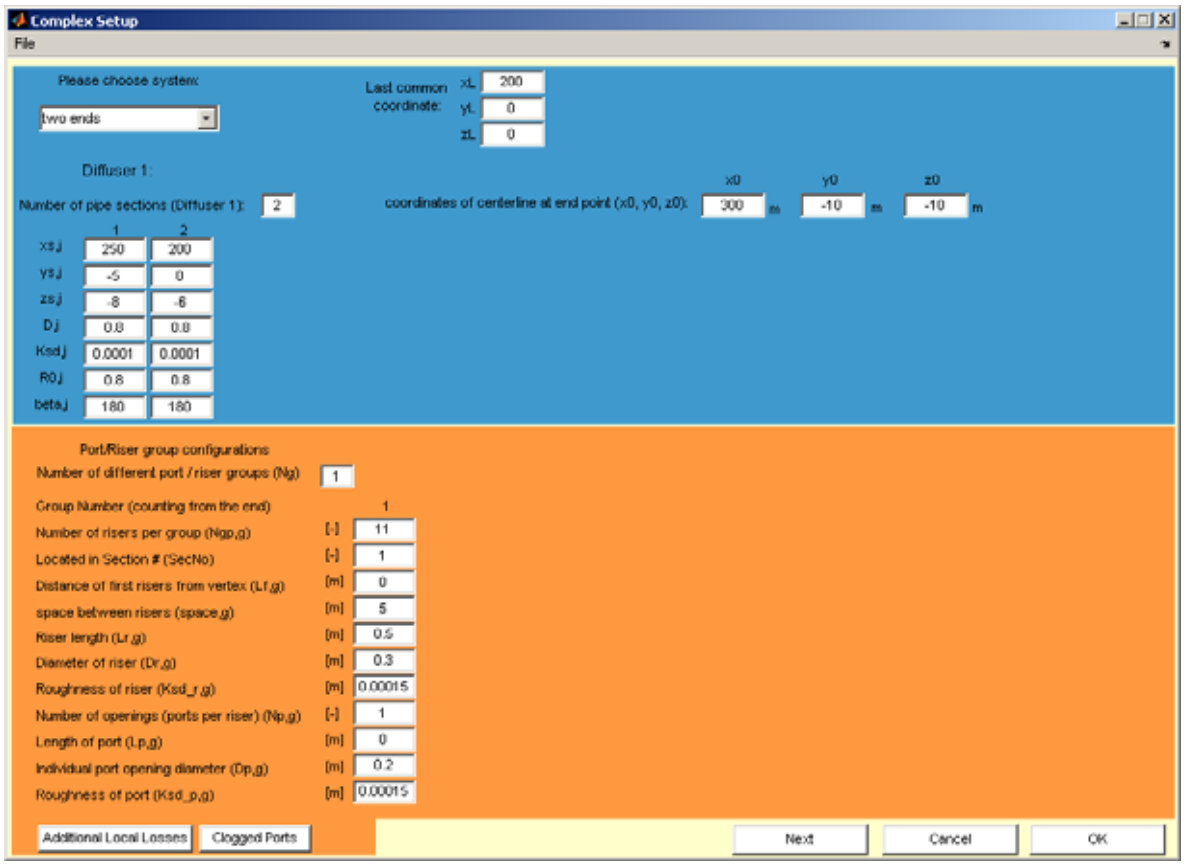

Complex Setup
File
Please choose system:
two ends
Last common coordinate:
xL 200
yL 0
zL 0
Diffuser 1:
Number of pipe sections (Diffuser 1): 2
coordinates of centerline at end point (x0, y0, z0):
x0 300 m
y0 -10 m
z0 -10 m
1 2
xs,j 250 200
ys,j -5 0
zs,j -8 -8
Dj 0.8 0.8
Ksdj 0.0001 0.0001
R0j 0.8 0.8
betaj 180 180
Port/Riser group configurations
Number of different port / riser groups (Ng) 1
Group Number (counting from the end) 1
Number of risers per group (Ngp,g) [-] 11
Located in Section # (SecNo) [-] 1
Distance of first risers from vertex (Lf,g) [m] 0
space between risers (space,g) [m] 5
Riser length (Lr,g) [m] 0.5
Diameter of riser (Dr,g) [m] 0.3
Roughness of riser (Ksd_r,g) [m] 0.00015
Number of openings (ports per riser) (Np,g) [-] 1
Length of port (Lp,g) [m] 0
Individual port opening diameter (Dp,g) [m] 0.2
Roughness of port (Ksd_p,g) [m] 0.00015
Additional Local Losses
Clogged Ports
Next
Cancel
OK

Fig. 19: First input sub-window for first diffuser part of Y- or T-diffuser

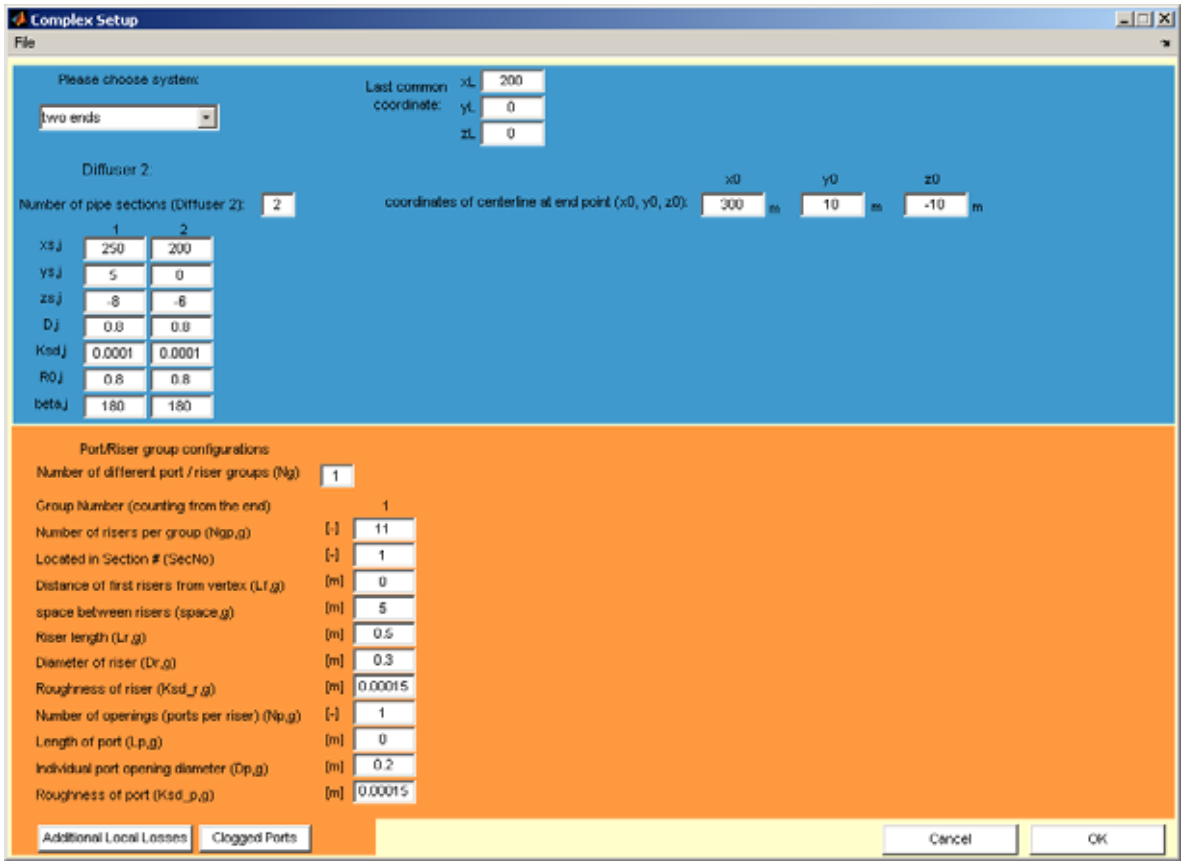

Complex Setup
File
Please choose system:
two ends
Last common coordinate:
xL 200
yL 0
zL 0
Diffuser 2:
Number of pipe sections (Diffuser 2): 2
coordinates of centerline at end point (x0, y0, z0):
x0 300 m
y0 10 m
z0 -10 m
1 2
xs,j 250 200
ys,j 5 0
zs,j -8 -8
Dj 0.8 0.8
Ksdj 0.0001 0.0001
R0j 0.8 0.8
betaj 180 180
Port/Riser group configurations
Number of different port / riser groups (Ng) 1
Group Number (counting from the end) 1
Number of risers per group (Ngp,g) [-] 11
Located in Section # (SecNo) [-] 1
Distance of first risers from vertex (Lf,g) [m] 0
space between risers (space,g) [m] 5
Riser length (Lr,g) [m] 0.5
Diameter of riser (Dr,g) [m] 0.3
Roughness of riser (Ksd_r,g) [m] 0.00015
Number of openings (ports per riser) (Np,g) [-] 1
Length of port (Lp,g) [m] 0
Individual port opening diameter (Dp,g) [m] 0.2
Roughness of port (Ksd_p,g) [m] 0.00015
Additional Local Losses
Clogged Ports
Cancel
OK

Fig. 20: Second input sub-window for second diffuser part of Y- or T-diffuser

5 Data Output

Before hitting the *Run* button, the user can choose the format of the output by checking the appropriate radio buttons in the upper right hand corner. Possible outputs include a diagram showing the selected configuration, a text file, a graph showing the energy and pressure grade lines, and a bar chart showing the riser discharges, diffuser velocities just upstream of every riser and the port velocities. When the *Run* button is hit, the data is read into variables and passed on to subprograms responsible for computation of discharges and pressures.

5.1 Report

If the report radio button has been activated for the output, an ASCII file is written to the program directory and consists of the following parts:

The header with the date:

```
Summary of the results
27-Apr-2005
--------------------------------------------------
--------------------------------------------------
```

Input data:

```
INPUT ambient data
Water level Hd [m] above datum (z = 0 m): Hd =
  4.00
Ambient density rho_0 in [kg/m³]
1000.00

--------------------------------------------------
INPUT effluent data
Density rho_e of effluent in [kg/m³]
999.00
Flowrate of effluent in [m³/s]
 33.62

--------------------------------------------------
INPUT outfall sections
Length, slope, x, y, and z coordinates for different sections
  #     Length  Slope     x       y       z
  -       -         -         7500.00          0.00   -2.50
  1     450.00    0.00  7050.00          0.00   -2.50
  2     500.00    0.00  6550.00          0.00   -2.50
  3     2050.00           0.00  4500.00          0.00   -2.50
  4     4480.00           0.00   20.00    0.00   -2.50
  5      21.03    0.31    0.00    0.00    4.00

--------------------------------------------------
```

Output data:

```
OUTPUT flowrates and velocities
Riser Discharges (q), Total discharge (Q), Port Velocities (Vp) and diameter (Dp), Jet
Velocities (Vj), Riser Velocities (Vr),
Densimetric Froude number, Diffuser diameter (Dd) & Diffuser Velocities (Vd) upstream
of port #
  #     q [m³/s]           Q [m³/s]       Vp[m/s] Dp[m]     Vj[m/s]   Vr    [m/s]    Fr[-]
        Vd [m/s] Dd [m]
  1     4.633519e-001  4.633519e-001  5.1034  0.170   5.1034  1.6388  124.9   0.3010  1.400
  2     4.595955e-001  9.229474e-001  5.0621  0.170   5.0621  1.6255  123.9   0.5996  1.400
  3     4.579980e-001  1.380945e+000  5.0445  0.170   5.0445  1.6198  123.5   0.8971  1.400
  4     4.558982e-001  1.836844e+000  5.0213  0.170   5.0213  1.6124  122.9   1.1932  1.400
  5     4.548185e-001  2.291662e+000  5.0095  0.170   5.0095  1.6086  122.6   1.4887  1.400
  6     4.550564e-001  2.746719e+000  5.0121  0.170   5.0121  1.6094  122.7   1.7843  1.400
  7     4.569866e-001  3.203705e+000  5.0333  0.170   5.0333  1.6163  123.2   2.0812  1.400
  8     4.610083e-001  3.664713e+000  5.0776  0.170   5.0776  1.6305  124.3   2.3806  1.400
...


--------------------------------------------------
OUTPUT riser locations - intersection with pipe centerline
  #       x       y       z
  1     7500.000        0.000  -2.500
  2     7450.000        0.000  -2.500
  3     7400.000        0.000  -2.500
  4     7350.000        0.000  -2.500
  5     7300.000        0.000  -2.500
  6     7250.000        0.000  -2.500
  7     7200.000        0.000  -2.500
  8     7150.000        0.000  -2.500
  9     7100.000        0.000  -2.500
```

```
 10     7050.000        0.000  -2.500
 11     7000.000        0.000  -2.500
....

--------------------------------------------------
OUTPUT losses and total head
_____________________________

Name of loss                                    Loss [m]       % of the relative head

Inlet head loss [m]                             0.080          1.3
Feeder head loss [m]                            5.141          81.4
Diffuser head loss [m]                          0.206          3.3
Av. port/riser headloss [m]                     0.069          1.1
        (Max. port/riser headloss [m]           0.226          3.6
        (Min. port/riser headloss [m]           -0.000         -0.0
Av. jet velocity head [m]                       0.196          3.1
        (Max. jet velocity head [m]             0.213          3.4
        (Min. jet velocity head [m]             0.184          2.9
Density head difference [m fresh water]         0.676          10.7
_____________________________________________________________________________
Sum of averages [m]                             6.368          100.8
        (Sum of all maximum losses [m]          6.543          103.6
        (Sum of all minimum losses [m]          6.287          99.5

Calc. relative total head, above sea level [m]      6.316
Calc. absolute total head [m]                       33.316


Losses in port/riser configuration at position i
  #     Headloss in port/riser [m]
  1      0.879
  2      0.905
  3      0.926
  4      0.962
  5      1.008
  6      1.067
  7      1.143
  8      1.236
....


--------------------------------------------------
OUTPUT design recommendations (Fischer et al, 1979)
(Sum of Area of ports cross-sections downstream) / (Area of diffuser cross sections)

  #       (Sum Ap(#))/Ad(#)
  1      0.059
  2      0.118
  3      0.177
  4      0.236
  5      0.295
  6      0.354
.....

END OF RESULTS
```

5.2 Graphical output

Fig. 21 shows the graphical output for a given flowrate Q_D and the calculated necessary total head H_t both written in the title of the graph. Absolute discharge values at every i-riser-position and the mean discharge are shown in the first bar-chart plotted against the x-coordinate -the distance from shoreline-. The second bar chart gives the relative discharge deviation, which is the ratio of individual riser discharge and the mean riser discharge minus one. A value of zero than means zero deviation from the mean riser discharge and a value of 0.1 means a 10 % deviation, which is also indicated. The allowable range of discharge variation can be modified by the user. In the same bar-graph also the port/riser headloss are printed on the second axis, because these are generally indicating the reason for strong discharge deviations. The third bar-chart indicates the port and jet velocities, which are interesting for further environmental impact analysis. The second axis in this graph shows the variation of port diameters along the diffuser. An additional information is given for a critical velocity, which is the one where the densimetric port Froude number equals unity. The fourth bar-chart indicates the velocities in the main diffuser pipe and a critical velocity when sedimentation might occur (default value of 0.5 m/s). As an additional information also the

feeder velocity is mentioned, if a feeder is applied. On the second axis of this graph the diffuser diameter variation along the diffuser is shown.

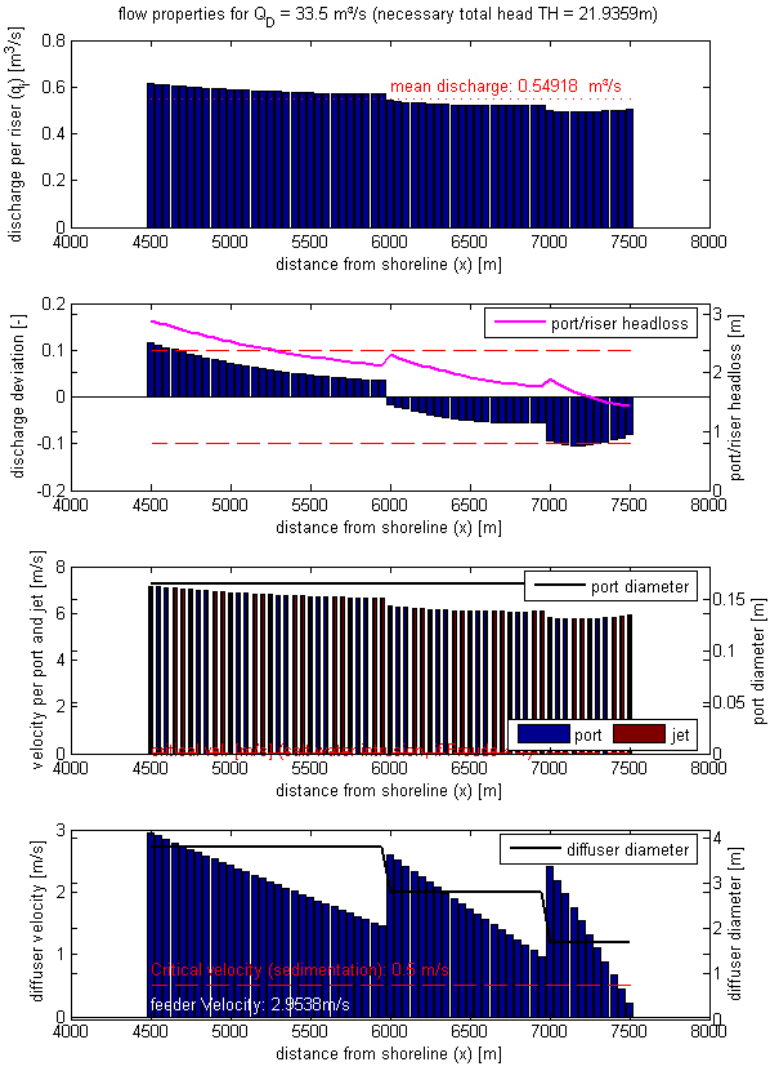


Fig. 21: Graphical output: bar charts showing the discharge per riser, the relative discharge deviation and port/riser headloss distribution, the discharge velocity at ports, the velocity in the diffuser pipe as well as port and diffuser diameter.

The second output (Fig. 22) describes the hydraulic and energy grade line (in fresh water heights) of the whole system. It indicates locations of major losses and shows the needed total head to drive the system (headworks head) as well as the total losses.

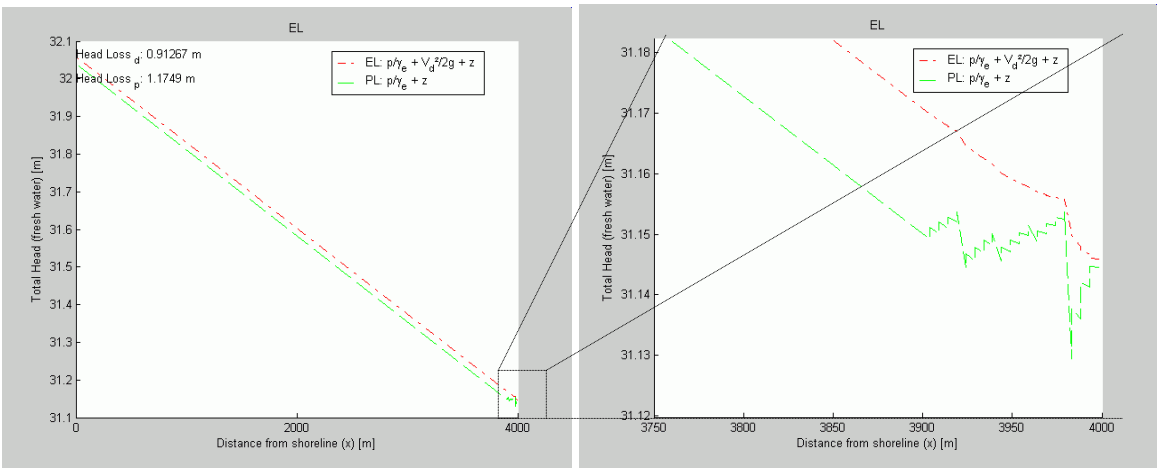

EL
Head Loss d: 0.91267 m
Head Loss p: 1.1749 m
EL: p/γe + Vd²/2g + z
PL: p/γe + z
Total Head (fresh water) [m]
Distance from shoreline (x) [m]
EL
EL: p/γe + Vd²/2g + z
PL: p/γe + z
Total Head (fresh water) [m]
Distance from shoreline (x) [m]

Fig. 22: Graphical output: Energy and Hydraulic grade line of the whole system and the diffuser

Graphical output for T-Diffuser: In progress

6 Design and optimization

The governing equation for the individual port discharge is equation (20). Equation (18) in (20) devided by q_i and squared gives:

$$1 = \frac{\frac{2}{\rho_e}\left(p_{d,i} - p_{a,i}\right) + 2g\left(z_{d,i} - z_{jet,i}\right) + \frac{\left(\sum_{k=1}^{i} q_k\right)^2}{A_{d,i}^{\,2}}}{\frac{q_i^2 \alpha_i^{\,2}}{\left(C_{c,i} A_{p,i}\right)^2} + \sum_{j=1}^{n_{p,i}} \left(\frac{q_i \alpha_i}{A_{p,i,j}}\right)^2 \left(\zeta_{p,i,j} + \frac{\lambda_{p,i,j} L_{p,i,j}}{D_{p,i,j}}\right) + \sum_{j=1}^{n_{r,i}} \left(\frac{q_i}{A_{r,i,j}}\right)^2 \left(\zeta_{r,i,j} + \frac{\lambda_{r,i,j} L_{r,i,j}}{D_{r,i,j}}\right)} \tag{24}$$

where the losses along the diffuser are included in the internal pressure $p_{d,i}$ from equation (18).

The first two terms in the numerator denote the difference of the piezometric head (hydraulic head) $\frac{2}{\rho_e}\left(p_{d,i} - p_{a,i}\right) + 2g\left(z_{d,i} - z_{jet,i}\right) = \Delta_i$ between the diffuser and the ambient. The third term in the numerator is related to the diffuser velocities $v_{d,i}$. The terms in the denominator are related to the jet velocity $v_{j,i} = \alpha_i q_i/(C_c A_{p,i})$ and the port and riser losses. For outfalls with uniform geometries or for uniform diffuser sections with uniform port/riser groups it follows $A_i = A = \text{const.}$, $\alpha_i = \alpha = \text{const.}$, $D_i = D = \text{const.}$, $L_i = L = \text{const.}$. Assuming a uniform flow distribution among the orifices gives $v_{r,i} = v_r$ and $v_{p,i} = v_p = \text{const.}$. Therefore all losses but the riser inlet loss and the port exit loss are constant ($\lambda_i = \lambda = \text{const.}$, $\zeta_{p,i} = \zeta_p$). Under these assumptions only few parameters change along the diffuser causing the variation of individual flows. The other parameters can be joint in constants C_i:

$$1 = \frac{\Delta_i + v_{d,i}^{\,2}}{C_1/C_{c,i}^{\,2} + C_2 \zeta_{dr,i}} \tag{25}$$

For diffuser without risers it is:

$$1 = \frac{\Delta_i + v_{d,i}^2}{C_1/C_{c,i}^2} \tag{26}$$

where C_1 and C_2 are constants for the whole diffuser or one diffuser section with equal port/riser configuration. The coefficients C_c and ζ_{dr} depend on the flow ratio of diffuser pipe flow and riser flow at each riser/port location, which is furthermore influenced by the pressure difference caused by Δ.

A design rule that is often mentioned in literature (Grace 1978), recommends to keep the ratio between the cumulative port areas $\Sigma^N_{k=1} A_{p,k}$ downstream a diffuser pipe cross section area $A_{d,N}$ smaller than one, with the explication that *"it is impossible to make a diffuser flow full if the aggregate jet area exceeds the pipe cross-section area, since that would mean that the average velocity of discharge would have to be less than the velocity of flow in the pipe"* (Fischer et al. 1979, p.419). A further suggestion taken from Fischer et al. (1979, p.419) resumes that the best ratio *"is usually between 1/3 and 2/3"*, $1/3 < \Sigma^i_{k=1} (A_{p,k}/A_{d,i}) < 2/3$. These criteria work fine for simple and uniform geometries without risers and for horizontal laid diffusers or for first estimates. But they can be unnecessarily conservative if no further optimization is done. For example sloped diffusers (following the sloped bathymetry) may equalize the distortion of the discharge profile resulting from a area ratio bigger than one. First estimates for non-uniform riser systems can be done by replacing the port cross-sectional area in the mentioned criteria with the riser cross-sectional area and applying these criteria for each section separately.

Nevertheless for changing geometries along the diffuser the previous criteria are not applicable in general. This, because 1) the diffuser velocities generally decrease along the diffuser or change considerably if tapering is applied, 2) the port/riser velocities may change if port/riser diameters are varied along the diffuser line causing a variation of C_c and 3) the flow distribution depends also on the losses along the diffuser, causing a variation of ζ_{dr}. For example, losses along the diffuser are considerably different for systems with same area ratio, but different number of openings.

Design rules regarding general loss ratios (Weitbrecht et al., 2002) for diffuser sections and downstream ports are also only applicable for simple geometries (no changes along the diffuser). For others, they are either unnecessarily conservative or not applicable, because losses are changing drastically along actual diffuser installations and cannot be summarized for the whole diffuser construction.

Therefore a design rule for non-uniform systems or for uniform sections and groups of a non-uniform system has to come out of a combination of a loss ratio (buoyancy and riser inlet (or port outlet) and a velocity ratio (diffuser velocity and branch velocity (port or riser)) (Equations (25), (26)). Furthermore sections and groups of a non-uniform system have to be balanced in between each other to achieve an overall uniform diffuser performance. The optimal procedure to organize these modifictions also under different flow conditions and further design criterias is described in the following chapters.

6.1 Far future design conditions

First design steps are either the usage of simple dilution equations (e.g. Jirka, 2003 or Jirka and Lee 1994) or the direct application of more detailed mixing models (e.g. CORMIX) under

given dilution requirements and major choices for the riser/port spacing to find a minimum diffuser length and a first port diameter estimate.

For example: The ambient standard is 100 times smaller than the effluent standard. Compliance has to be assured outside the mixing zone of 10 times the average water depth. This demands for discharges at around 15 m depth an effluent dilution of 100 at 150 m downstream the plume. Cormix calculations including a sensitivity analysis with the included program CorSens allow to optimize the general diffuser characteristics for that case (e.g. diffuser of 100 m length, 10 ports and a port diameter of $D_p = 0.2$ m).

Step 1: Baseline calculation - Far future design conditions

- The data from the first successful mixing calculations is used as first design alternative for the internal hydraulics
  - ⇒ run CorHyd with very few diffuser and port/riser sections and plot results
- Pipe velocities: Diffuser, riser and port velocities should be in between reasonable ranges, otherwise the diameters have to be increased or decreased generally for all sections and/or groups ($V_d < V_r < V_p < V_j$)
  - ⇒ modify feeder/diffuser diameter to obtain operable velocities (0.5 m/s < V_d < 5 m/s)
  - ⇒ modify riser diameters to obtain operable velocities (0.5 m/s < V_r < 5 m/s)
  - ⇒ modify port diameters to obtain operable velocities (0.5 m/s < V_p < 12 m/s) at least at the majority of port/riser configurations
- Total head: The necessary total Head or the final flow should be in the desired order of magnitude, otherwise velocities and/or locations of high losses should be reduced
  - ⇒ simplify geometries and/or increase diameters to reduce the total head
- Flow distribution:
  - ⇒ check whether the flow distribution lies in between reasonable limits ($q_{min} = -0.1q_i/N < q_i < 0.1q_i/N = q_{max}$) for at least the majority of port/riser configurations
  - ⇒ modify riser diameters for the whole diffuser to obtain a more homogeneous distribution of the riser inlet losses
  - ⇒ modify port diameters for the whole diffuser to obtain a more homogeneous distribution of the port losses (i.e. if Duckbills are applied)
- Check external hydraulics with modified diffuser
- If either the external hydraulics or even the modified internal hydraulics do not fulfill the general requirements listed above the user should try to do a re-design of the main diffuser characteristics. Else proceed to the optimization in step 2.

6.2 Boundary condition variations

CorHyd does include an automatic routine for considering a varying effluent flow or varying total head respectively and varying ambient water level elevations. The user therefore has to change the time_series values from 0 to 1 in the run.m file. CorHyd than calculates all parameters for every situation and writes the results in report files and gives a summarized graphical output in addition to the output for the design condition.

Varying flowrates
All headlosses, with the exception of the "buoyancy headloss" are almost proportional to the squared flow velocity. This means that the flow distribution along the diffuser is the same for all values of the the total flow, if density differences are neglectable and/or the diffuser is not sloped. Considerable density differences in combination with sloped diffusers cause different flow distribution for different total flows. Due to the constant influence of sloping on the discharge profile the profile asymptotically approaches the non-sloped profile for increasing total discharges.

Under low-discharge conditions, diffuser are confronted especially with issues of scouring and/or intrusion of seawater. Seawater intrusion can seldomly be avoided for all discharges. Duckbill valves and small diameter pipes prevent those problems, but lead to additional pumping costs or higher headwork storage buildings. Intrusion can be prevented if the port densimetric Froude number is bigger than 1: $F_p = V_p/(\Delta\rho/\rho g D_p)^{0,5} > 1$ (Wilkinson, 1988), where V_p denotes the port exit velocity and D_p the port diameter, resulting in a critical port velocity $V_{p,crit} = (\Delta\rho/\rho g D_p)^{0,5}$. For discharges, where it is not possible to meet this criterion, saltwater enters the system leading to unsteady two-layer flow. To describe these processes detailed numerical or physical modeling has to be performed.

Varying ambient conditions
Varying the ambient water level elevation or the density does generally not affect the flow distribution along the diffuser, but only the necessary total head to drive the system. Maximum and minimum values for ambient water level elevation and density should be analysed whether they may cause operational problems or the necessity of higher storage buildings.

Step 2: Diffuser characteristics - diffuser performance calculations

- Analyse diffuser performance for intermediate flows
  ⇒ run CorHyd time-series for varying discharges and plot results
- Pipe velocities: time-series results allow to denote diffuser sections, where scouring velocities are too low for most of the flowrates and/or where port Froude numbers are below or near unity.
  ⇒ create additional diffuser sections at positions, where scouring velocities are not obtained for discharges which occur once a day
  ⇒ create additional port/riser groups for added diffuser sections (starting with the same geometry).
  ⇒ modify diffuser section diameters locally (tapering) to obtain scouring velocities
- Flow distribution: check whether the flow distribution lies in between reasonable limits ($q_{min} = -0.1q_i/N < q_i < 0.1q_i/N = q_{max}$) for at least the majority of port/riser configurations
  ⇒ modify the riser group diameters locally
  ⇒ modify port group diameters locally
  ⇒ introduce additional port/riser groups if necessary and repeat local modifying
- Check external hydraulics with modified diffuser
- If either the external hydraulics or even the modified internal hydraulics do not fulfill the general requirements as listed above the user should try to do a re-design of the main diffuser characteristics. Else proceed to the optimization in step 3.

6.3 Off design conditions

It was common practice to design diffusers only for the final design flow, which often caused long-term malfunctions during low-flow periods. A common technique to overcome this problem are “expanding diffusers” (Avanzini, 2003), that are designed to meet the initial and final requirements by either closing initially a certain number of ports (either with fixed closures or backpressure regulations, which open autonomous if enough discharge enters the system (Avanzini, 2003)) and or modifying port diameters using replaceable flanged orifices (Bleninger et al., 2004). Therefore the number of necessary discharging ports for near future flowrates have to be evaluated. Generally half discharge allows to close more than half of the ports, without the need of modifying the operational scheme. Mixing model calculations may show, that less ports are necessary during near future flowrates to comply with environmental standards. It is therefore recommended to close the landward ports during diffuser construction and open these ports after the flowrates increased over the near-future value.

CorHyd allows to analyse the diffuser performance for these scenarios by simply closing the ports. Furthermore it is often easier and cheaper to operate the diffuser under these conditions than operating the final diffuser with low flows. A flowrate meter at the outfall inlet has to be installed to record when the modification of the diffuser has to be done and more or all ports have to be opened.

Furthermore accidents like pipe ruptures due to anchor collisions, earthquakes or structural failures can be analyzed by adding the accidental holes with their estimated area transformed into an equivalent diameter. Vice-versa test can be made by knowing the water level elevation in the headworks, the flowrate and the basecase geometry, and looking for the dimension of the rupture.

Step 3: Off-design calculation - near future design conditions

- Near-future mixing calculations are used to figure out the number of necessary ports for low flow discharges.
  ⇒ run CorHyd with clogged ports and plot results
- Analyse pipe velocities, and the flow distribution, if the final diffuser configuration with clogged ports allows to discharge near-future flows under reasonable conditions.
  ⇒ modify the number and the location of the clogged ports to optimize near-future flow conditions
- Check external hydraulics with modified diffuser
- If either the external hydraulics or even the modified internal hydraulics do not fulfill the general requirements as listed above the user should try to do a re-design of the main diffuser characteristics. Else proceed to the optimization in step 4.

6.4 Sensitivity Analysis

Numerical calculations are often based on simplified formulations and non accurate input data, both containing uncertainties, which have to be considered in the results and if possible limited to certain ranges. Quantitative results as obtained with CorHyd at first look seem to promise high accuracies, but have to be seen as results within a standard deviation which may vary significantly if compared to laboratory data, field data or model data from other

numerical methods. The design process therefore has to foresee a sensitivity analysis to avoid huge “errors” and to be aware of possible variations.

Influence of formulation inaccuracies
Especially if complex geometries are applied the influence of the formulations for loss coefficients has to be checked carefully. As shown in 2.4.1 all loss formulations are based on empirical studies mostly calibrated in laboratory investigations. Therefore it is recommended to do calculations with additional loss coefficients especially for the port/riser configurations and check whether the influence on diffuser performance are important or not. If the influence is big, it is recommended to do laboratory studies to find better formulations for this special configuration.

Influence of construction imprecision
Submarine construction techniques do not allow for precise pipe allocation and precise pipe fittings. Therefore loss coefficients calculated out of loss formulations may have uncertainties due to non-precise siting and fitting of the pipes. Additional losses are resulting out of these uncertainties. Consequences are higher losses. These can be estimated using the formula from 2.4.1 for inaccurate sitings and fittings. Sensitivity studies on these uncertainties allow for analysis of maximum total head level.

Varying material properties
Additionally changes of materials over time can be considered in further sensitivity calculations, where pipe roughness values can be increased and diffuser performance be analysed (Wood et al, 1993, p. 133). If deposition of solids is expected decreased diameters allow to analyse diffuser performance under these condition.

Step 4: Sensitivity analysis - prediction accuracy

- Final diffuser design under maximum discharge conditions
  - ⇒ run CorHyd with additional port losses to check influences of loss formulations on final result
  - ⇒ vary geometrical details to check influences of construction imprecision on final result
  - ⇒ add additional losses on whole pipe-system to account for imprecision
  - ⇒ vary material properties to check influences of deterioration
- Check external hydraulics with modified diffuser

Table 5 summarizes the effects on a reference case for the discharge profile and the total head, if the observed parameters are increased. It is distinguished between horizontal and sloped diffusers where either the port elevations are at constant depth or varying along the diffuser.

Table 5: Sensitivity of involved parameters on head loss, total head and homogeneity of the discharge profile.

Increasing the … :	leads to … of the total head or the discharge distribution resp.	
	Total Head	**Homogeneity**
Total discharge (no slope)	↑↑	0
- " - (with slope)	↑↑	↓↓ or ↑↑
Ambient water depth (no slope)	↑↑	0
- " - (with slope)	↑↑	↓ or ↑
Density difference (no slope)	↑	↑
- " - (with slope)	↑	↓ or ↑
Feeder length	↑	0
Diffuser length (constant total length)	↓↓	↓
Diffuser pipe diameter	↓↓	↓ or ↑
Pipe roughness	↑	0
Number of risers (constant diffuser length)	↓	0
Riser spacing (variable diffuser length)	↓↓	↓
Riser height	↑	0
Ports per riser	↓	↓
Port diameter	↓	↓↓
Flexible valves	↑↑	↑↑

↑ / ↓	=	moderate in- / decrease
↑↑ / ↓↓	=	strong in- / decrease
0	=	neutral or small changes

In summary, the above procedure that obviously requires some analyst intervention and adjustment, seems to be reasonably unambiguous and straightforward.

7 Case studies

To demonstrate CorHyd capabilities the outfall from Ipanema in Rio de Janeiro, Brazil, has been chosen as base case. The outfall design is herein compared with typical other constructional configurations as they would be applied in actual designs.

Furthermore a case study of the planned outfall for Buenos Aires (Argentina) is shown to analyse diffuser hydraulics for very long diffusers (here 3 km).

Finally comparisons with conventional diffuser programs indicate the necessity of the implemented extensions of CorHyd.

7.1 Ipanema - Rio de Janeiro - Brazil

The Ipanema outfall in Rio de Janeiro, Brazil, operates since 1975 and discharges actually about 6 m³/s (+/- 1 m³/s daily variation, from 2.1 mio. people) coarse screened domestic sewage from the southern part of the city into the coastal waters of the Atlantic ocean (Fig. 23, Carvalho, 2003). The outfall was designed for an average discharge of 8 m³/s (equivalent 4.0 mio. people) with peak discharges up to 12 m³/s. The outfall is made of a 4326 m long

concrete pipe with a diameter of 2.4 m including a 449 m long diffuser section with 90 ports on each side of the pipe, each with a nominal diameter of 0.17 m, a spacing of 5 m and pointing downwards with an angle of 45° to the horizontal (Carvalho et al., 2002, Fig. 24 and Fig. 25). The diffuser is in a depth of about 27 m. The slope of the diffuser line could not be found in literature. The Ipanema outfall is one of the few outfalls which have been monitored in detail, with special emphasize on mixing characteristics (Carvalho et al., 2002). These monitoring studies showed in general good mixing characteristics. At commissioning 59 of the 180 ports have been closed on purpose to achieve reasonable flow conditions until design flow is reached. Since 1996 all ports are discharging. The constructional design itself is unusual, with a concrete diffuser line fixed on piles above the seabed. The piles proofed to be the weak point of the construction, where pile breaks lead to a major rupture in year 2000. Today simpler and cheaper laying methods are available (e.g. HDPE pipes with weights or laid in a trench), which promise to be more resistant to dynamic wave forcing and currents.

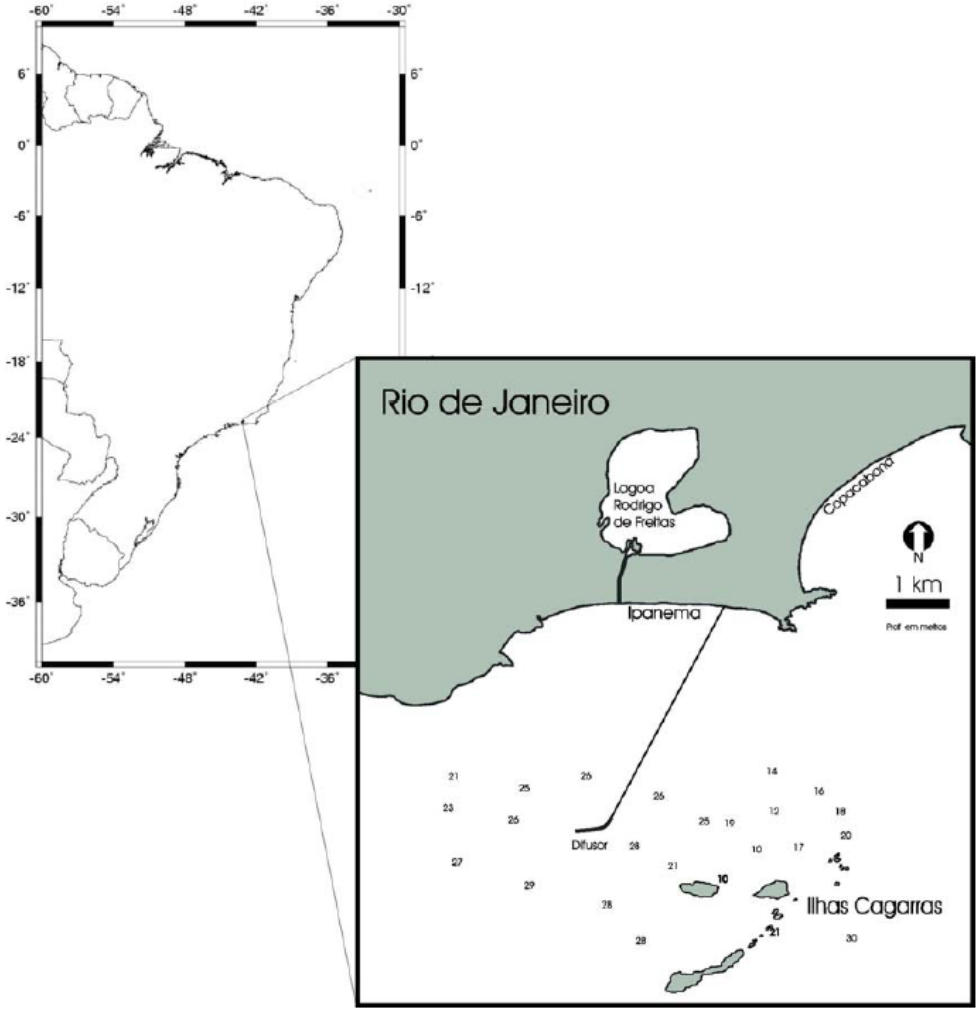


Fig. 23: Locoation map of the Ipanema outfall of the city Rio de Janeiro in Brazil (Carvalho, 2003).

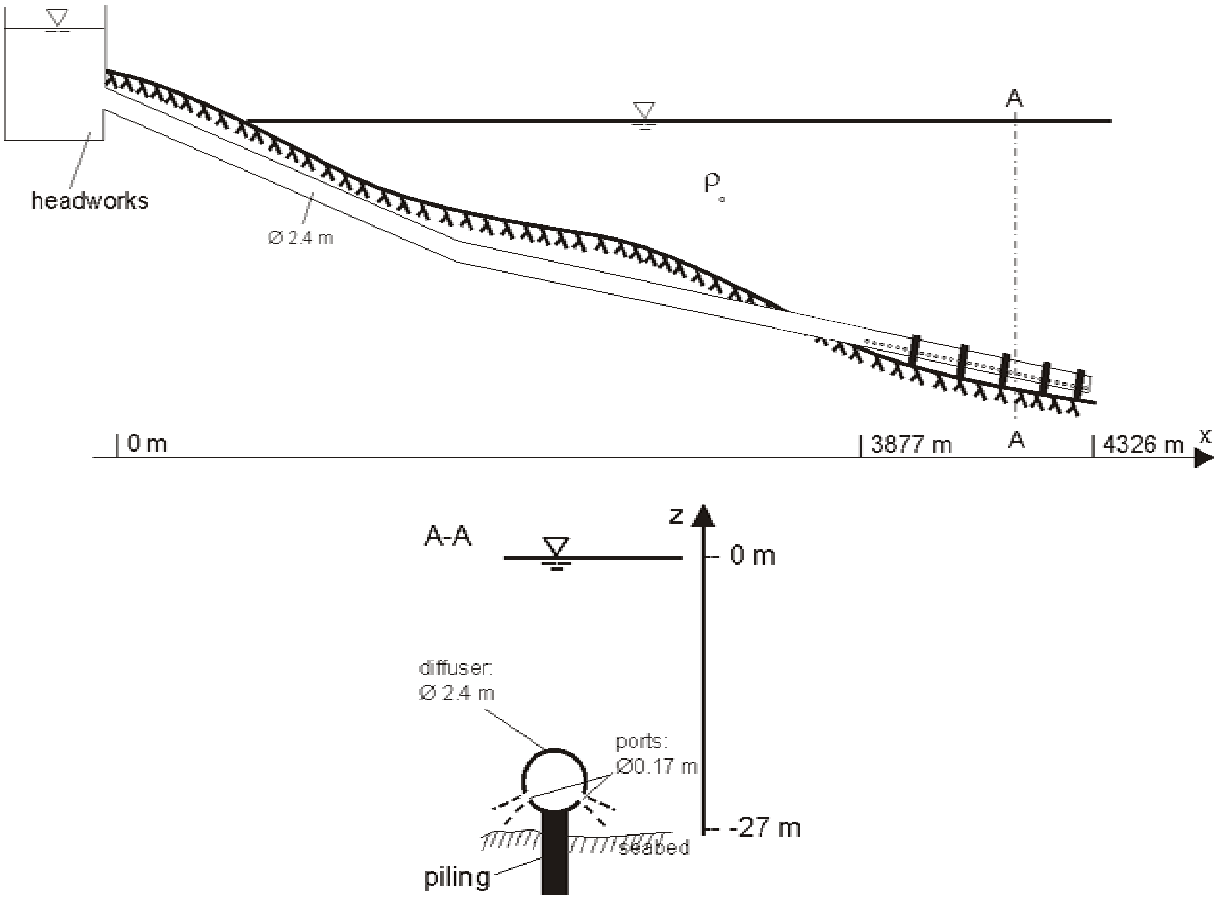


Fig. 24: Side view and cross section of the Ipanema outfall.

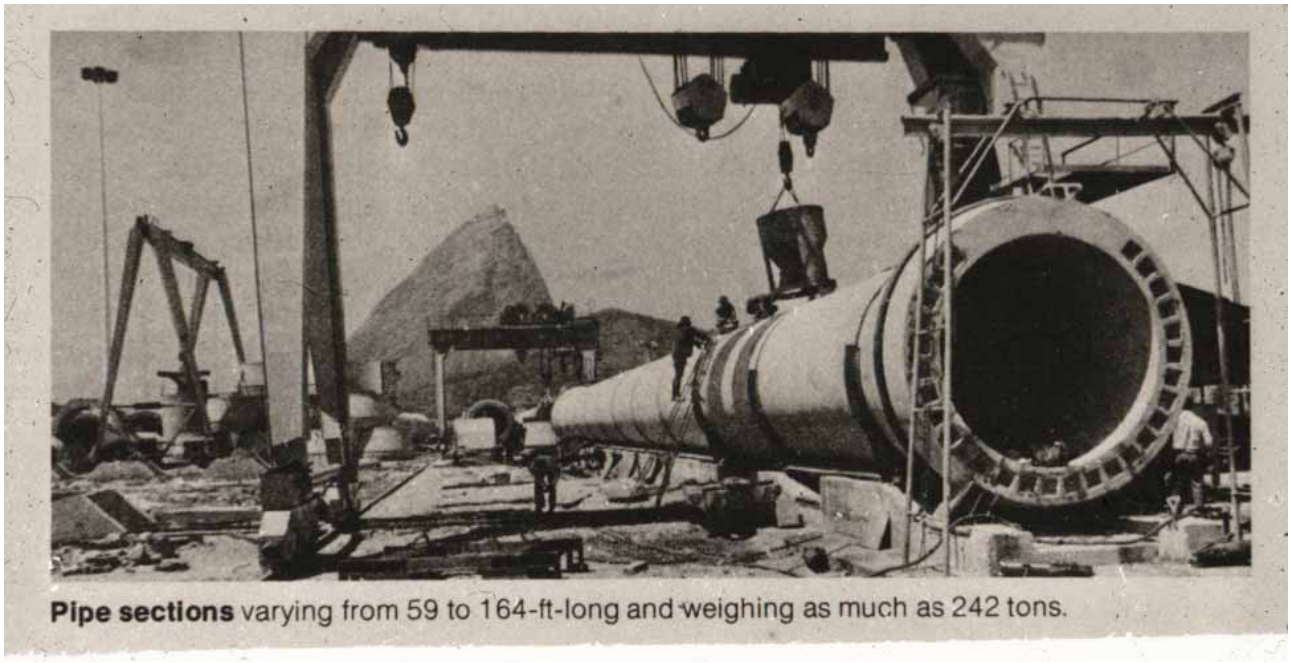


Fig. 25: Image from the construction site of the Ipanema outfall

The calculated internal flow characteristics are summarized in Fig. 26 for design flow $Q_d = 8$ m³/s and a horizontal (left hand side) or sloped diffuser line (right).

A reasonably good discharge distribution along the diffuser (first bar-chart, Fig. 26) with maximum deviations from the mean discharge of not more than 5 % of the mean discharge (second bar-chart, Fig. 26) is obtained. Due to different pressure losses along the diffuser pipe and the port/riser configurations (line in second bar-chart, Fig. 26) the discharge is increasing here to the seaward end. Usually diffuser cannot be laid horizontally as assumed here, because of the sloping bathymetries. Therefore another calculation is shown in Fig. 26 on the right side, with a sloped diffuser with an assumed elevation difference of 3 m along the diffuser length of 449 m (= 6.7 ‰). The discharge deviation in this case is almost neglectable, which is due to a higher pressure difference between the sewage in the diffuser pipe and the heavier ambient water especially in deeper waters at the seaward diffuser end.

The flow velocities in the diffuser pipe continuously decrease in seaward direction (fourth bar-chart, Fig. 26). For the last 25 port locations velocities below 0.5 m/s are predicted, which might cause sedimentation of particles in the diffuser. This number reduces for peak flows (Q = 12 m³/s), (Fig. 27), to about 16 but still the last 75 m of the diffuser have velocities much lower than 0.5 m/s. That means, that even for maximum discharges scouring velocities are not obtained for the end part of the diffuser. Considering, that the present treatment is only coarse screening, this might cause problems for the diffuser end part.

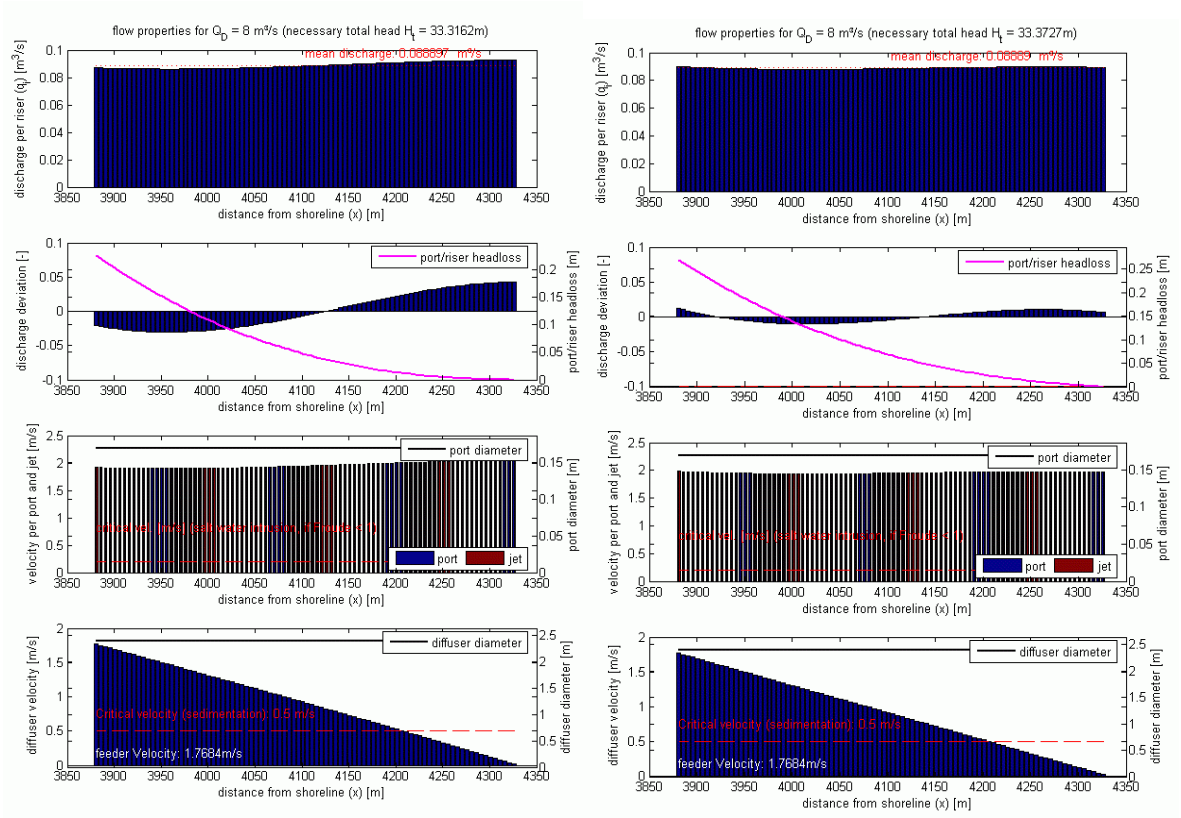

flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.3162m)
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.3727m)
discharge per riser (q_i) [m³/s]
mean discharge: 0.088897 m³/s
mean discharge: 0.08889 m³/s
distance from shoreline (x) [m]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 1.7684m/s
diffuser diameter [m]

Fig. 26: Flow characteristics for design flow. Left: horizontal diffuser, right: sloped diffuser 3m/449m. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

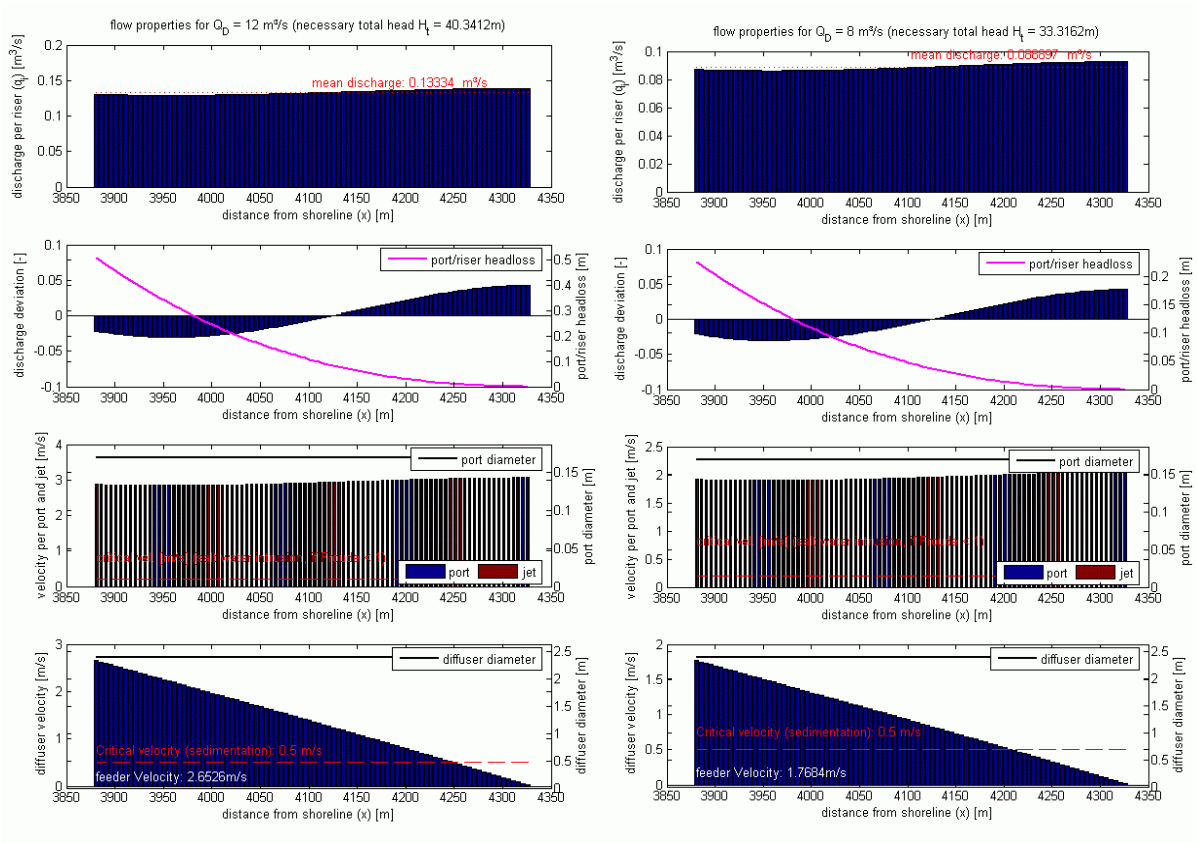

flow properties for Q_D = 12 m³/s (necessary total head H_t = 40.3412m)
mean discharge: 0.13334 m³/s
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.3162m)
mean discharge: 0.088897 m³/s
discharge per riser (q_i) [m³/s]
distance from shoreline (x) [m]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
diffuser diameter [m]
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 2.6526m/s
feeder Velocity: 1.7684m/s

Fig. 27: Flow characteristics for different flows. Left: maximum flow Q_{max} = 12 m³/s, right: design flow Q_d = 8 m³/s. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

Fig. 28 shows the flow characteristics for several intermediate flowrates. A slight variation of the discharge distribution can be observed for these flow variations only for the sloped diffuser. The changes of the total head for increasing discharges are shown in Fig. 29. But the most critical point stays the low scouring velocity, which affects almost 40 % of the diffuser (169 m and about 60 ports) for the flowrate of 6 m³/s, which is presently the average flow.

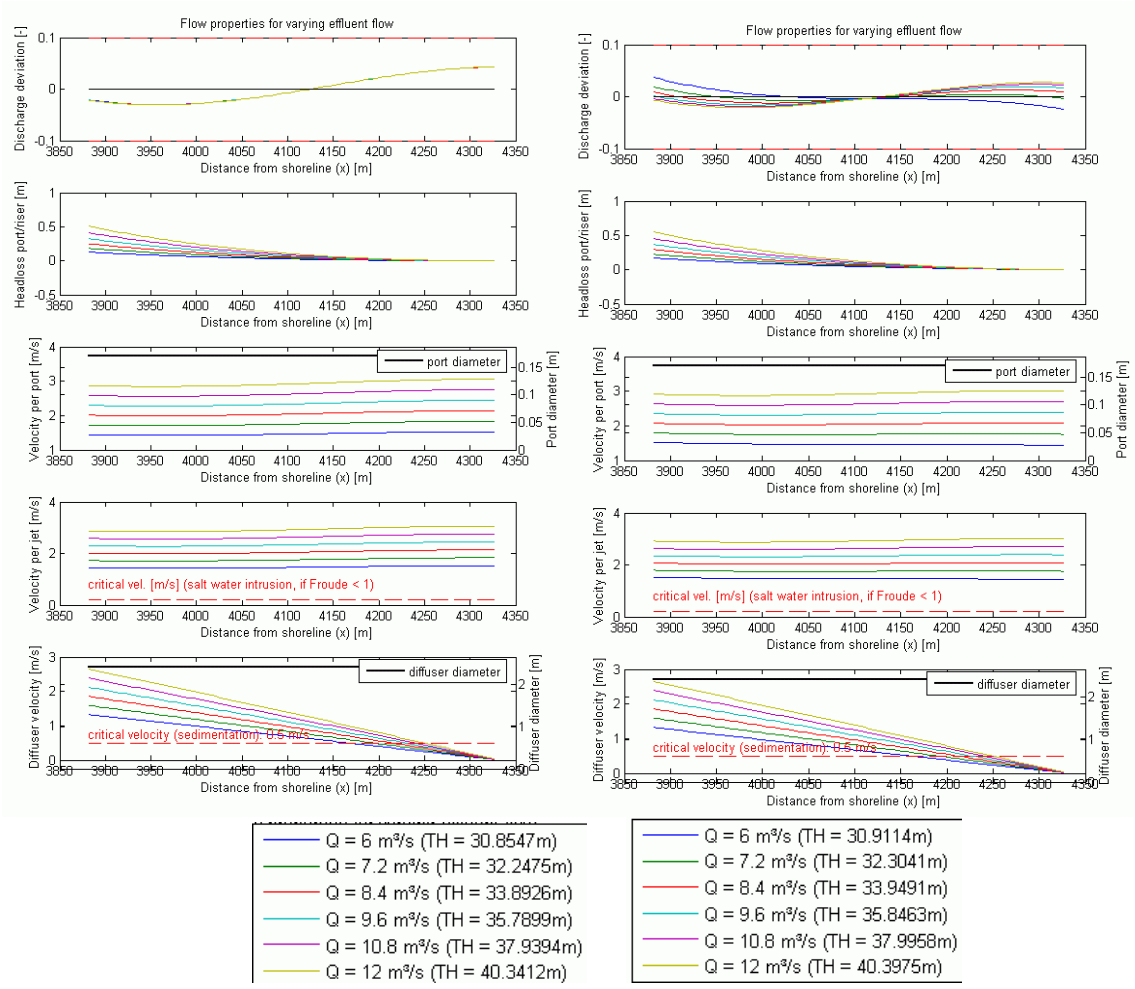

Flow properties for varying effluent flow
Discharge deviation [-]
Distance from shoreline (x) [m]
Headloss port/riser [m]
Velocity per port [m/s]
port diameter
Port diameter [m]
Velocity per jet [m/s]
critical vel. [m/s] (salt water intrusion, if Froude < 1)
Diffuser velocity [m/s]
diffuser diameter
Diffuser diameter [m]
critical velocity (sedimentation): 0.6 m/s
Q = 6 m³/s (TH = 30.8547m)
Q = 7.2 m³/s (TH = 32.2475m)
Q = 8.4 m³/s (TH = 33.8926m)
Q = 9.6 m³/s (TH = 35.7899m)
Q = 10.8 m³/s (TH = 37.9394m)
Q = 12 m³/s (TH = 40.3412m)
Q = 6 m³/s (TH = 30.9114m)
Q = 7.2 m³/s (TH = 32.3041m)
Q = 8.4 m³/s (TH = 33.9491m)
Q = 9.6 m³/s (TH = 35.8463m)
Q = 10.8 m³/s (TH = 37.9958m)
Q = 12 m³/s (TH = 40.3975m)

Fig. 28: Flow characteristics for different discharges (Q), left: horizontal diffuser, right: sloped diffuser 3m/449m, showing the riser flow deviation, port/riser headloss, port and jet discharge velocities, diffuser pipe velocities and total head (H_t)

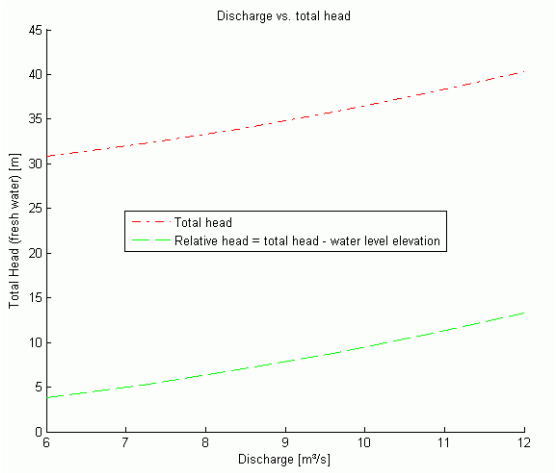

Discharge vs. total head
Total Head (fresh water) [m]
Discharge [m³/s]
Total head
Relative head = total head - water level elevation

Fig. 29: Changes in total head for varying discharges vs. constant ambient water level.

Before 1996 the diffuser was operated with lesser ports, because 59 of 180 have been closed due to low design discharges. Fig. 30 shows the flow properties for this modified diffuser

under different flow conditions. The performance is equal the one for higher flows and more ports.

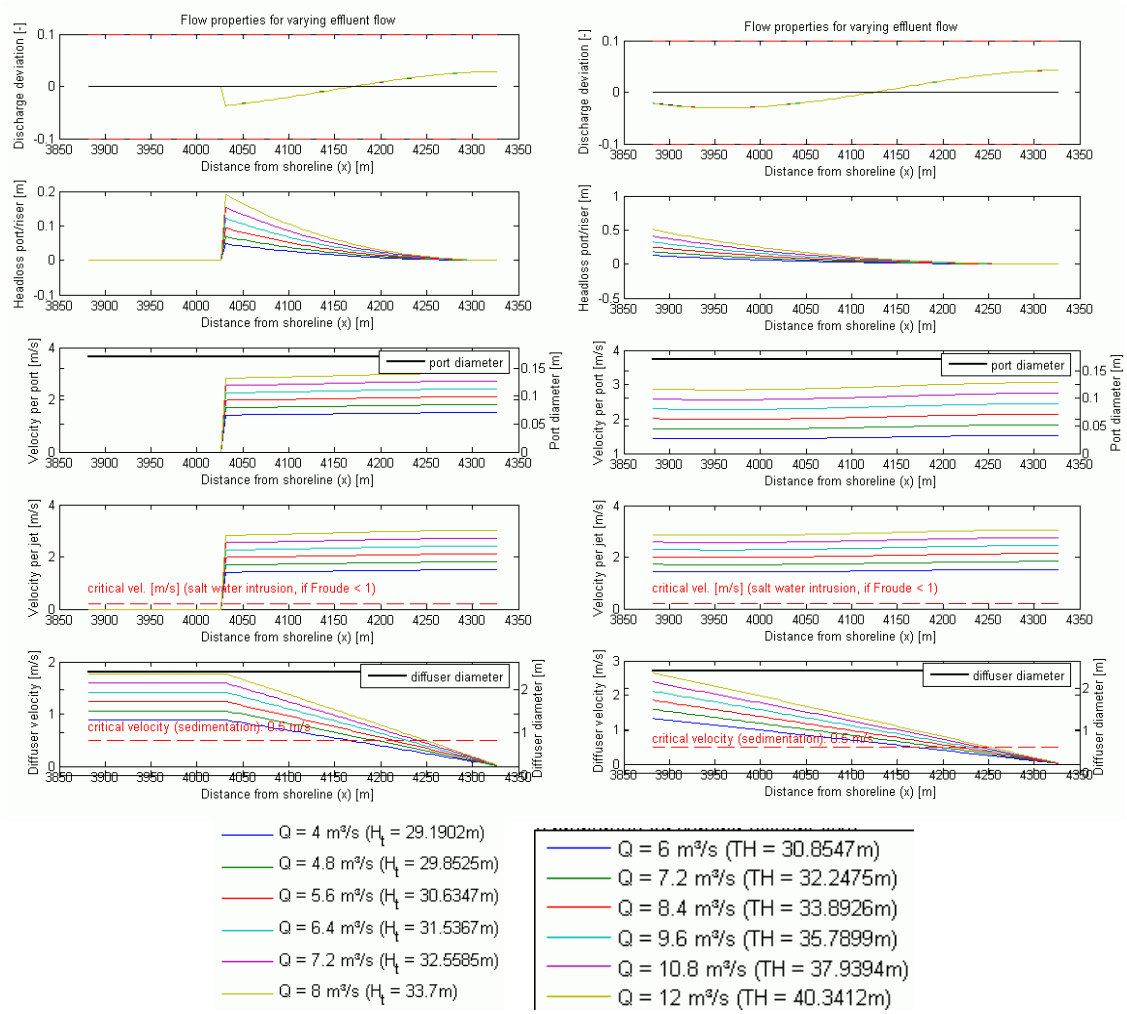

Flow properties for varying effluent flow
Discharge deviation [-]
Distance from shoreline (x) [m]
Headloss port/riser [m]
Velocity per port [m/s]
port diameter
Port diameter [m]
Velocity per jet [m/s]
critical vel. [m/s] (salt water intrusion, if Froude < 1)
Diffuser velocity [m/s]
diffuser diameter
Diffuser diameter [m]
critical velocity (sedimentation) 0.5 m/s
Q = 4 m³/s (Ht = 29.1902m)
Q = 4.8 m³/s (Ht = 29.8525m)
Q = 5.6 m³/s (Ht = 30.6347m)
Q = 6.4 m³/s (Ht = 31.5367m)
Q = 7.2 m³/s (Ht = 32.5585m)
Q = 8 m³/s (Ht = 33.7m)
Q = 6 m³/s (TH = 30.8547m)
Q = 7.2 m³/s (TH = 32.2475m)
Q = 8.4 m³/s (TH = 33.8926m)
Q = 9.6 m³/s (TH = 35.7899m)
Q = 10.8 m³/s (TH = 37.9394m)
Q = 12 m³/s (TH = 40.3412m)

Fig. 30: Flow characteristics for different discharges (Q), left: 59 of 180 ports closed, right: all ports open, showing the riser flow deviation, port/riser headloss, port and jet discharge velocities, diffuser pipe velocities and total head (H_t)

Changes in the ambient water level do not have any effect on the flow characteristics but increase the total head. To prevent intrusion of ambient water (including sediments), especially during low flow, the port densimetric Froude number should be bigger than unity: $F_p = V_p/(\Delta\rho/\rho g D_p)^{0,5} > 1$ (Wilkinson, 1988), where V_p denotes the port exit velocity and D_p the port diameter. This gives a critical port velocity $V_{p,crit} = (\Delta\rho/\rho g D_p)^{0,5} = 0.041$ m/s for Ipanema outfall. All port and jet exit velocities (third bar-chart, Fig. 28) are considerably higher for all applied flowrates.

7.1.1 Diffuser optimization

Scouring velocities

The present geometry does not allow for scouring velocities in the end part of the diffuser. The maximal flow, which occurs actually once a day is 7 m³/s. The last 150 m of the diffuser do have too low velocities under this condition. Therefore a taper is introduced at exactly this position and the diameter reduced from 2.4 m to 1.2 m. This reduces the pipe section with velocities lower than 0.5 m/s to 25 m (10 ports). Under peak discharge (12 m³/s) there are

only 10 m (4 ports) where velocities are lower. Negative consequences of the taper is a higher head (5 % increase of the relative head) and a more distorted discharge distribution.

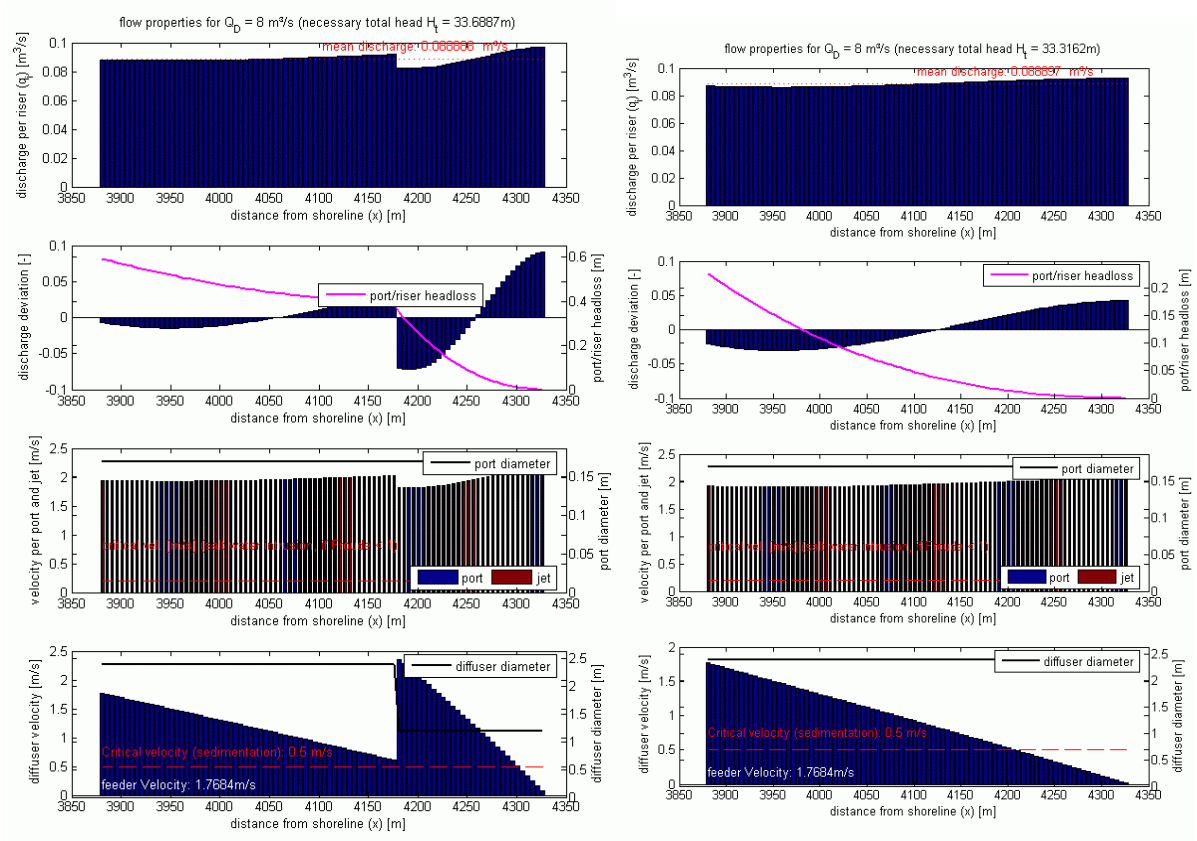

flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.6887m)
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.3162m)
mean discharge: 0.088896 m³/s
mean discharge: 0.088897 m³/s
discharge per riser (q_i) [m³/s]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
diffuser diameter [m]
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 1.7684m/s
distance from shoreline (x) [m]

Fig. 31: Flow characteristics for tapered diffuser. Left: reduced diffuser diameter of 1.4 m for end part, right: basecase, both for design flow Q_d = 8 m³/s. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

Constructional alternatives

The piling of the diffuser pipe caused problems due to broken piles and therefore leakage at diffuser pipe joints. State of the art constructional design alternatives would try to avoid these problems by using a HDPE pipe with concrete weights fixing the diffuser on the ground. The internal hydraulics would be affected by only by minor differences in roughness.

a) Covered diffuser or in trench - short risers

If wave forcing, sediment transport or navigation and fishing activities are a major problem for the diffuser pipe, it also can be covered (Fig. 32) or laid in a trench (Fig. 33). In both cases short risers have to be used to connect the buried pipe with the ambient water. The riser pipes with the two attached ports are causing additional losses and therefore distort the discharge profile, especially due to the previous tapering causing different riser/diffuser ratios and therefore non-uniform distributions (Fig. 34). Increasing the riser diameter in the tapered diffuser end part allows to equilibrate these additional changes, because the additional separation losses depend on the diameter ratio between diffuser pipe and riser pipe. The risers therefore have a diameter of 0.3 m at the end part and of 0.2 at the near-shore part of the diffuser. In this case the only change is a little increase in total head of about 4 % compared to the tapered diffuser with no risers and 10 % compared to the basecase (Fig. 34).

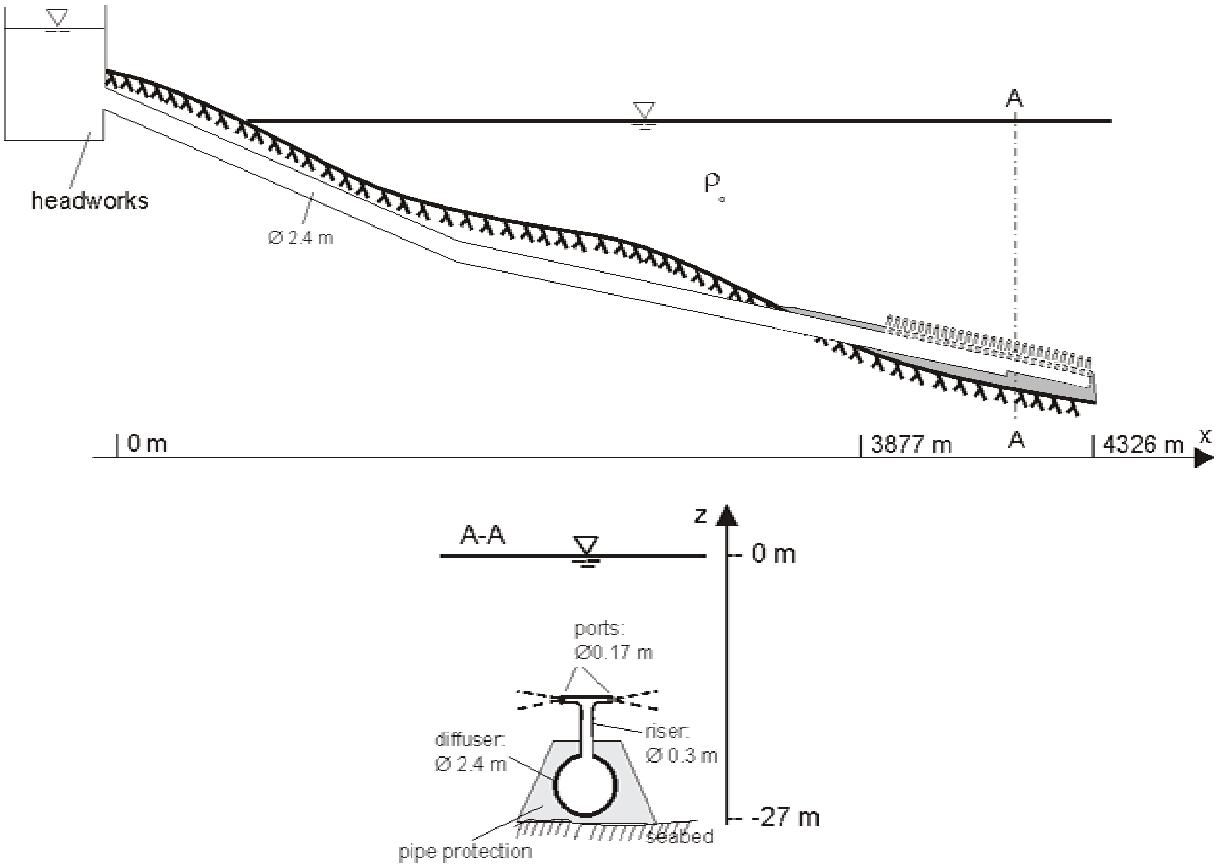


Fig. 32: Side view and cross section of a constructional design alternative for the Ipanema outfall with a covered diffuser pipe and short risers.

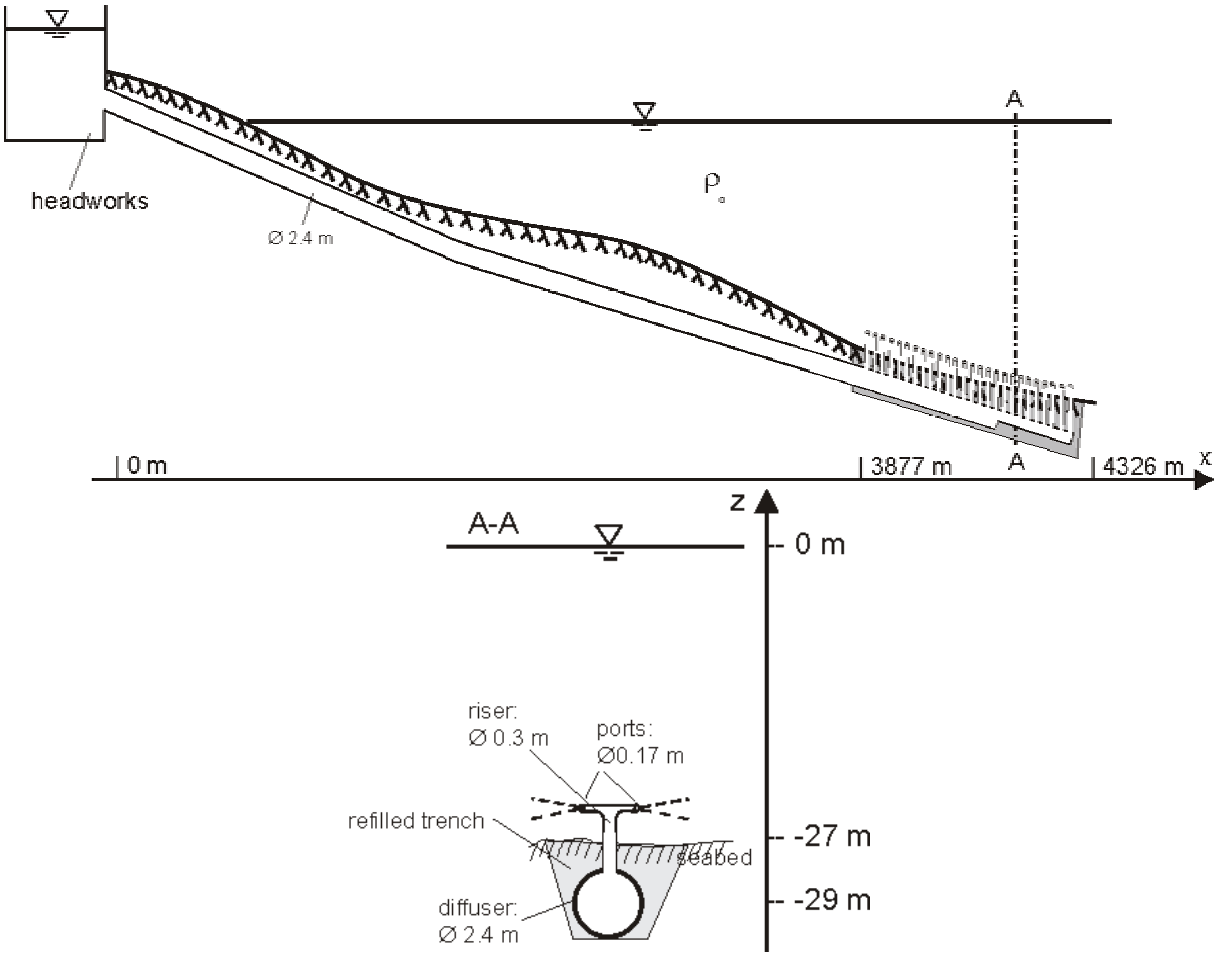


Fig. 33: Side view and cross section of a constructional design alternative for the Ipanema outfall with a diffuser pipe laid in a refilled trench and short risers.

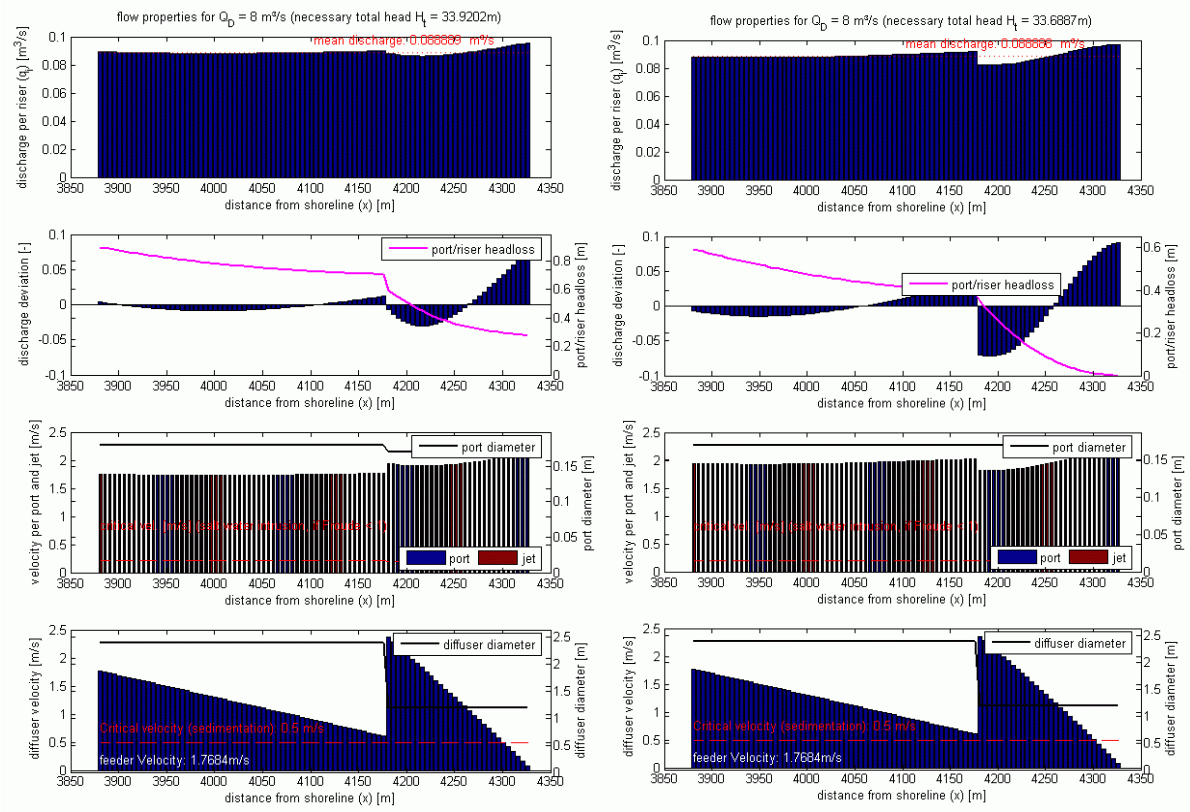

flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.9202m)
mean discharge: 0.066666 m³/s
discharge per riser (q_i) [m³/s]
distance from shoreline (x) [m]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 1.7684m/s
diffuser diameter [m]
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.6887m)
mean discharge: 0.066666 m³/s

Fig. 34: Flow characteristics for: Left: tapered diffuser covered or laid in a trench with additional short risers, right: tapered diffuser on piles without risers, both for design flow Q_d = 8 m³/s. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

These differences especially caused by the local losses of the flow entering a riser and further additional loss formulations would not result out of existing diffuser programs (e.g. Fischer et al., 1979, implemented as code PLUMEHYD; and Wood et al., 1993, implemented as DIFF). The design and the important optimization of the riser diameters, is not possible in other programs, although influences on design parameters are huge.

a) Tunneled diffuser - long risers

Nowadays tunneled outfalls are also affordable in some cases. Often long risers have to used in these circumstances (Fig. 35). To achieve a more homogeneous discharge distribution the riser diameters have to be modified: 0.35 m in the end part and 0.25 at the near-shore part of the diffuser. Fig. 36 shows the flow characteristics for a tunneled diffuser with long risers. The more homogeneous flow distribution causes that the total head compared to the previous case is even a bit smaller.

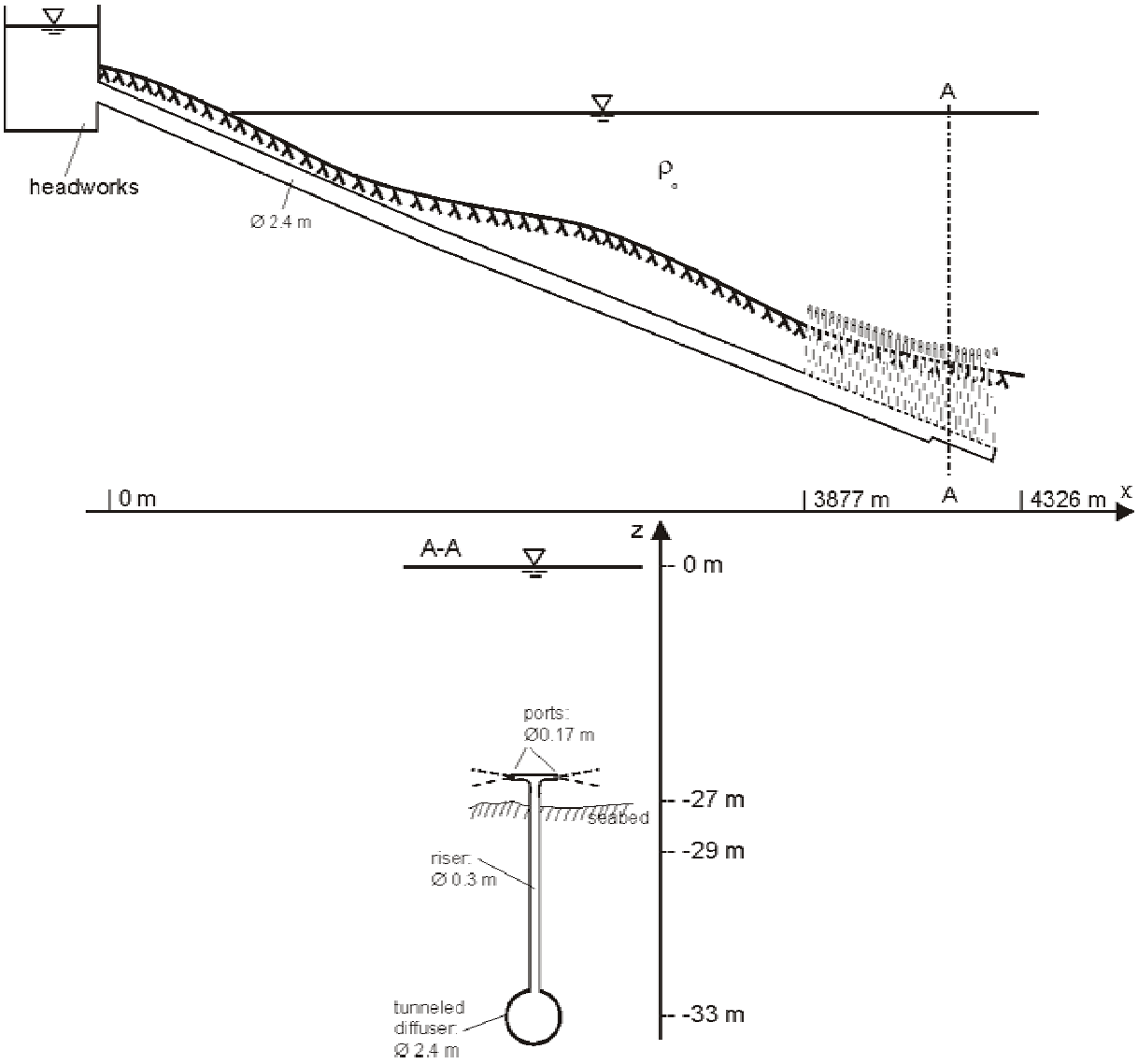


Fig. 35: Side view and cross section of a constructional design alternative for the Ipanema outfall with a tunneled diffuser pipe and long risers.

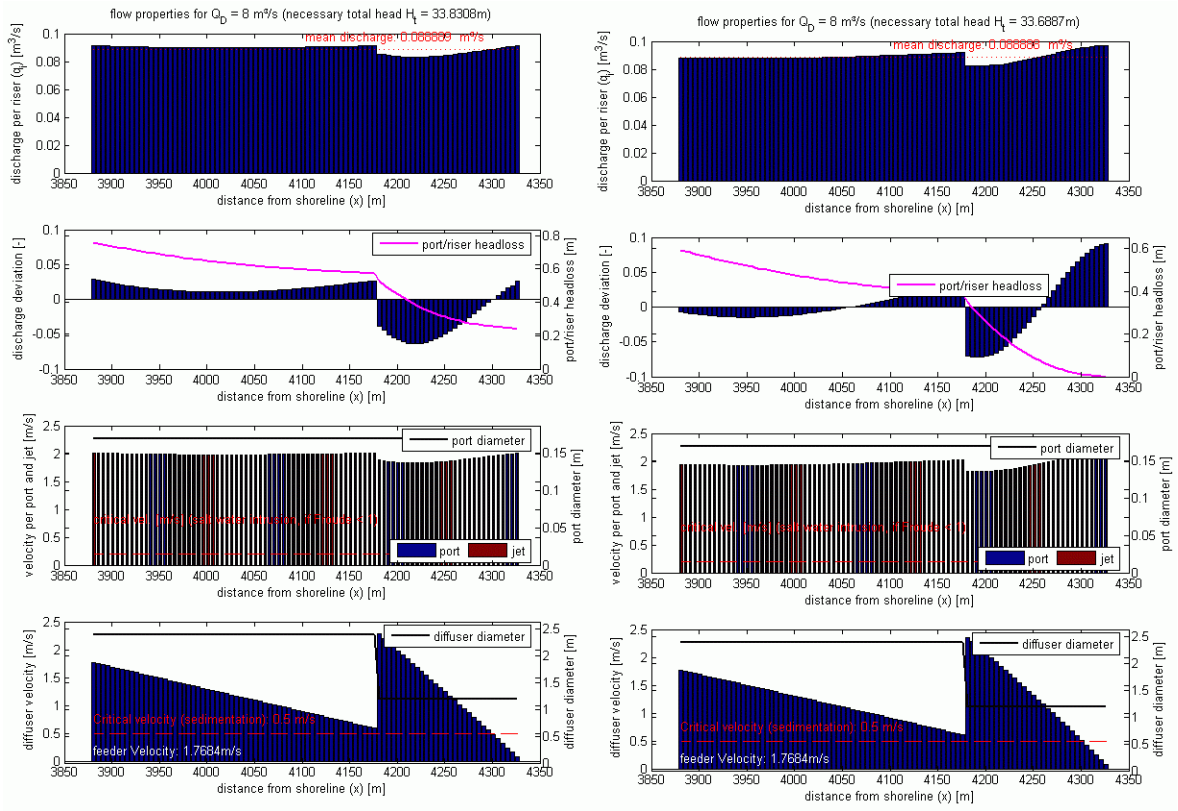

flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.8308m)
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.6887m)
discharge per riser (q_i) [m³/s]
distance from shoreline (x) [m]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
diffuser diameter [m]
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 1.7684m/s

Fig. 36: Flow characteristics for: Left: tapered tunneled diffuser with long risers, right: tapered diffuser on piles without risers, both for design flow Q_d = 8 m³/s. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

a) Tunneled diffuser - long risers and rosette like port arrangements

In the case of tunneled outfall it is furthermore tried to reduce the number of risers, because these drilling operations are quite expansive. Instead of many risers a few huge risers with rosette like port arrangements at the top are constructed (Fig. 41). The flow characteristics for the tapered tunneled diffuser with long riser and a rosette like port arrangement, using half of the risers and having four ports discharging at every rosette are shown in Fig. 38. The riser diameters have been increased to cope with the increased flowrate to 0.6 m at the tapered diffuser end and 0.35 m at the near-shore part of the diffuser. Fig. 38 shows also, that the internal flow characteristics seem to be similar, and also the total head is even a bit smaller.

Furthermore it has to be considered, that the application of few rosettes compared to many risers does have an non neglectable effect on the external hydraulics. A detailed mixing zone calculation should be analyzed to study this drastic change of the diffuser geometry.

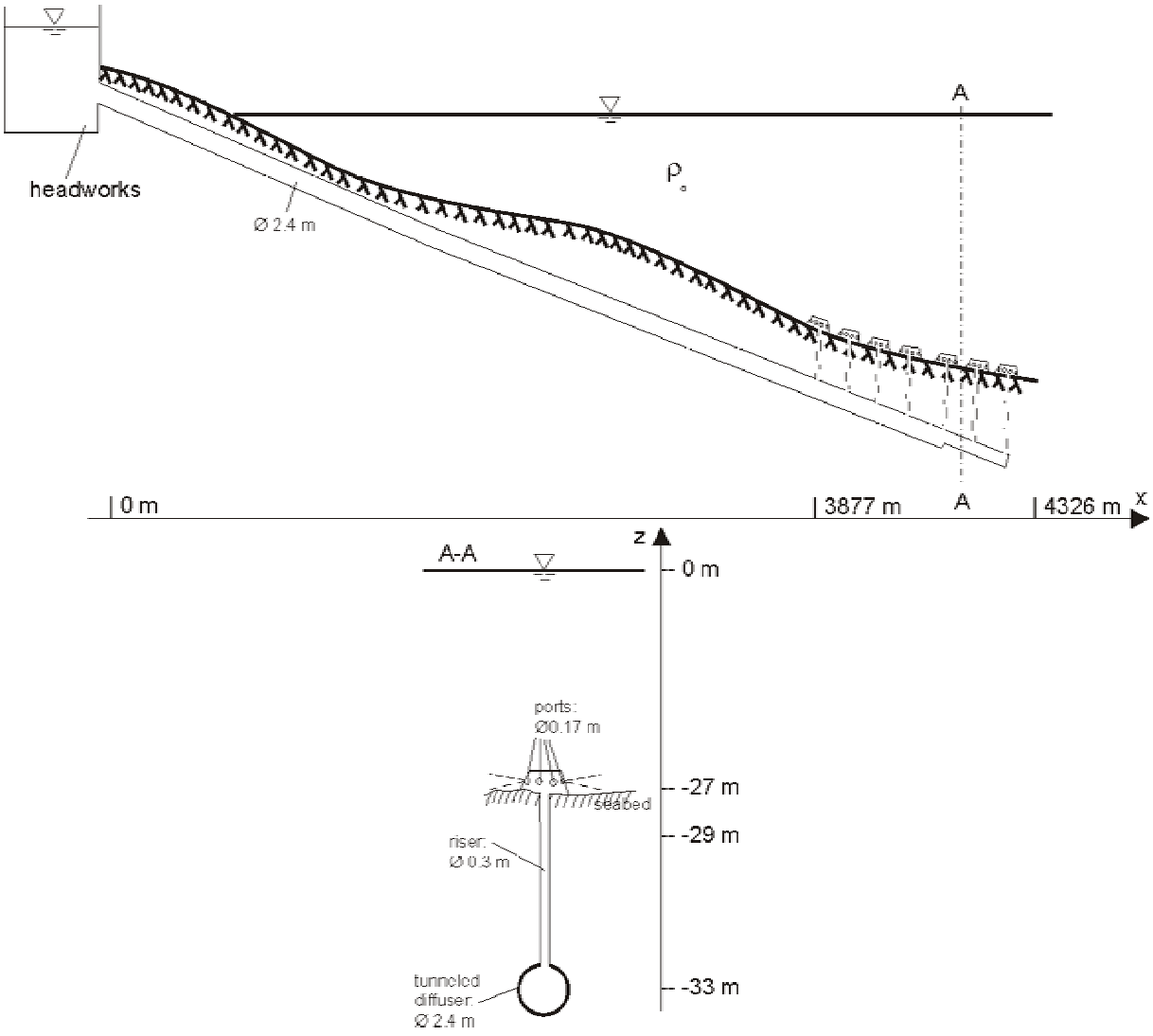


Fig. 37: Side view and cross section of a constructional design alternative for the Ipanema outfall with a tunneled diffuser pipe, long risers and rosette like port arrangements.

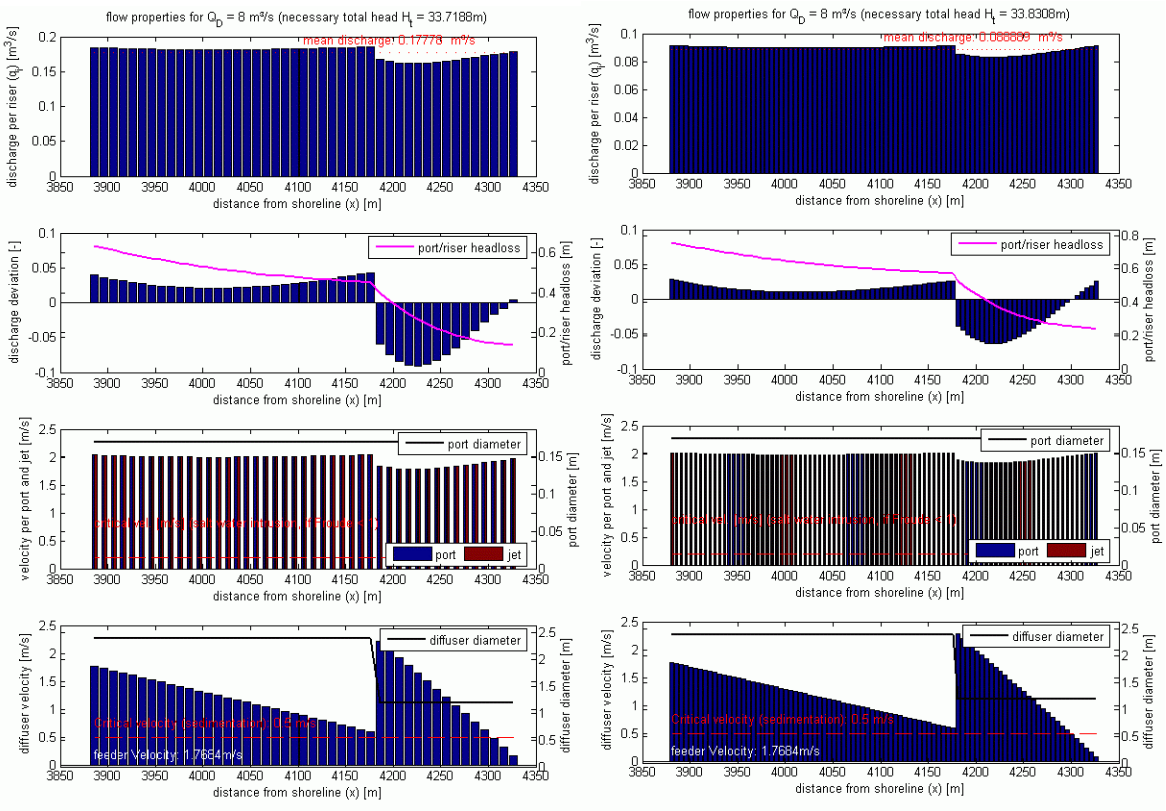

flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.7188m)
mean discharge: 0.17778 m³/s
discharge per riser (q_i) [m³/s]
distance from shoreline (x) [m]
flow properties for Q_D = 8 m³/s (necessary total head H_t = 33.8308m)
mean discharge: 0.088889 m³/s
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 1.7684m/s
diffuser diameter [m]

Fig. 38: Flow characteristics for: Left: tapered tunneled diffuser with long riser and rosette like port arrangements, right: tapered tunneled diffuser with long risers, both for design flow Q_d = 8 m³/s. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines)

a) Duckbill valves - variable area orifices

Existing diffusers may also be modified by attaching variable area orifices (Duckbill valves, DBV) to avoid intrusion of saltwater, debris or sediment as well as to make the discharge distribution more homogeneous during low flows. Fig. 39 shows a time-series run for a system with duckbill valves compared to a system without. Improvements of the discharge profile are especially seen for low flows, which is even more effective for sloped diffusers. Beside the additional costs for Duckbill valves also an increased total head has to be considered (11 % increase compared to same system without duckbills and 14 % compared to basecase).

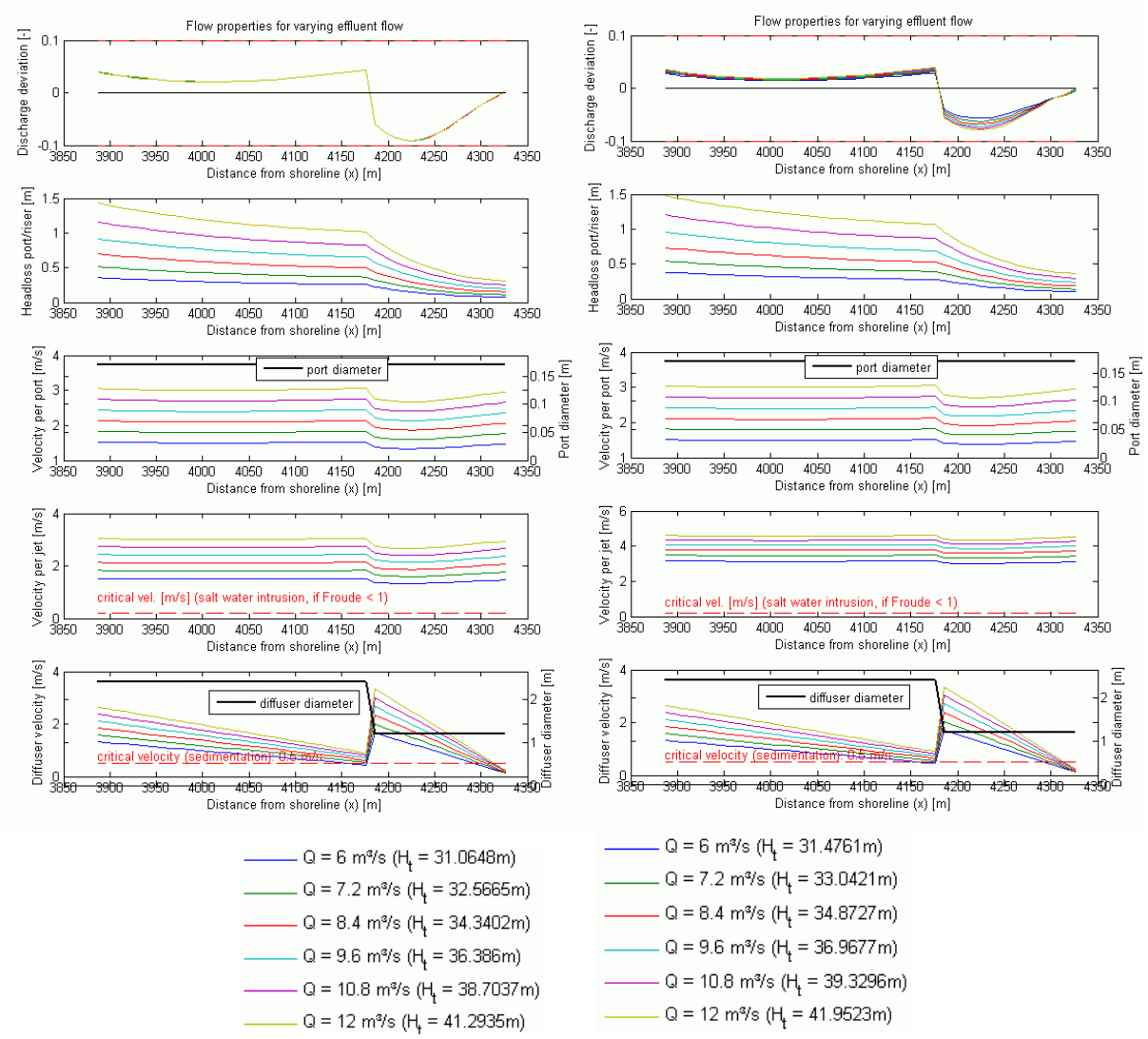

Flow properties for varying effluent flow
Discharge deviation [-]
Distance from shoreline (x) [m]
Headloss port/riser [m]
Velocity per port [m/s]
port diameter
Port diameter [m]
Velocity per jet [m/s]
critical vel. [m/s] (salt water intrusion, if Froude < 1)
Diffuser velocity [m/s]
diffuser diameter
Diffuser diameter [m]
critical velocity (sedimentation) 0.5 m/s
Q = 6 m³/s (Ht = 31.0648m)
Q = 7.2 m³/s (Ht = 32.5665m)
Q = 8.4 m³/s (Ht = 34.3402m)
Q = 9.6 m³/s (Ht = 36.386m)
Q = 10.8 m³/s (Ht = 38.7037m)
Q = 12 m³/s (Ht = 41.2935m)
Q = 6 m³/s (Ht = 31.4761m)
Q = 7.2 m³/s (Ht = 33.0421m)
Q = 8.4 m³/s (Ht = 34.8727m)
Q = 9.6 m³/s (Ht = 36.9677m)
Q = 10.8 m³/s (Ht = 39.3296m)
Q = 12 m³/s (Ht = 41.9523m)

Fig. 39: Flow characteristics for different discharges (Q), left: tunneled tapered diffuser with long risers and rosette like port arrangement, right: same with additional Duckbill valves (D = 200 mm), showing the riser flow deviation, port/riser headloss, port and jet discharge velocities, diffuser pipe velocities and total head (H_t)

Table 6 shows the comparison between the different alternatives listed above. An optimized diffuser design often results in an increased total head. Maximum values are here a 15 % increase. But often cheaper solutions in the order of 5 % allow for very good diffuser performance and result in lesser maintenance necessities and better dilution characteristics and therefore cheaper operation.

Table 6:Comparison of constructional alternatives for Ipanema diffuser

name	total head / relative head [m]	difference in total head to basecase [m / %]	discharge distribution [%]	no scouring [m] / [no. of ports] (L_d = 449, 180 ports)
basecase (build)	33.32 / 6.32	0 / 0	+/- 5	125 m / 50
taper	33.69 / 6.69	0.37 / 6	+/- 8	20 m / 8
taper short riser	33.92 / 6.92	0.60 / 9.5	+/- 8	20 m / 8
taper long riser	33.83 / 6.83	0.50 / 7.9	+/- 5	20 m / 8
taper long riser rosettes	33.72 / 6.42	0.4 / 6.2	+/- 8	20 m / 12
taper DBV 200	34.23 / 7.23	0.91 / 14.4	+/- 6	20 m / 12

7.2 Berazategui - Buenos Aires - Argentina

The Berazategui outfall is planned to discharge the treated effluents of a waste water treatment plant to be constructed for the city of Buenos Aires. The sewer-system is separated from the rainfall canalisation and is designed for an average effluent flowrate of about 25 m³/s with a maximum peak discharge of 33.5 m³/s. The outfall starts at the pumping basin on the onshore headworks, from where a 4500 m long feeder tunnel conveys the effluent to the 3000 m long diffuser in the disposal area (Fig. 40). The diffuser is composed of vertical risers carrying four ports in a rosette-like arrangement (Fig. 41).

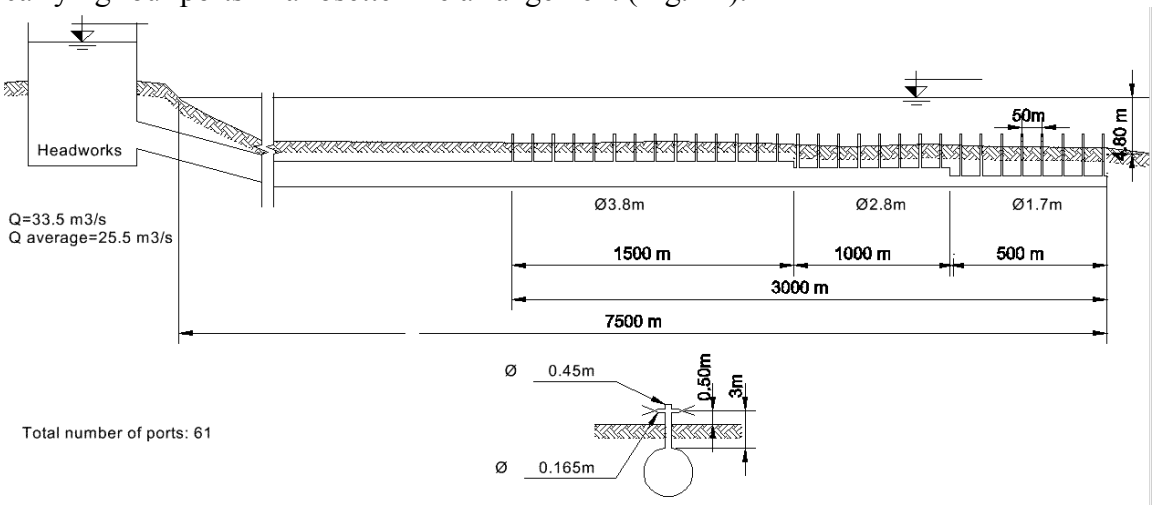


Fig. 40: Schematic view of diffuser longitudinal section of Berazategui outfall

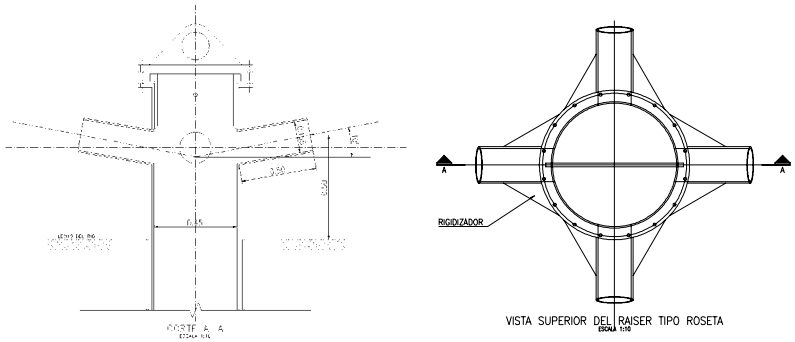


Fig. 41: Side and top view of riser/port configuration of diffuser

The receiving water body is the Rio de la Plata estuary of the rivers Paraná and Uruguay (average annual fresh water discharge: 23,000 m³/s). The width of the estuary at the outfall location is about 50 km with a depth varying from 4 to 7 m (Fig. 42). Tidal currents, including temporal density stratifications dominate the velocity field (average local velocity: v = 0.04 m/s, maximum velocities during tidal cycle v_{max} = 0.3 m/s).

Fig. 42: Top view of the Rio de la Plata delta showing the location of the Berazategui outfall and the ambient characteristics at its location *(source: Nasa, 2005)*

These very special ambient conditions are not unique and can be found also in other shallow coastal regions of the world (e.g. China Sea or Baltic Sea), where also outfalls are planned or already operating. But design and control of these outfalls are difficult, because existing design guidelines (Grace, 1978; Williams, 1985; Water Research Centre, 1990; Wood et. al., 1993; UNEP, 1996) are limited to deep water disposal sites.
The complex dispersion patterns of the 3 km wide diffuser plume in an unsteady shallow environment and the internal hydraulics of the construction itself are a major challenge for engineering design and predictive mixing and transport models. However, this paper will focus on the internal hydraulics of the Berazategui outfall installation considering the flow partitioning and related pressure losses in the manifold resulting in a discharge profile along the diffuser. The external environmental hydraulics, which deal with the effluent mixing with the ambient fluid are not discussed here.

The calculated internal flow characteristics are summarized in Fig. 43 for maximum flow Q_{max} = 33.5 m³/s and in Fig. 44 for several smaller flows (all left hand side). These are compared with results for the same geometry, but with attached duckbill valves with the nominal diameter of 150 mm (right hand side).
A reasonably good discharge distribution along the diffuser (first bar-chart Fig. 43) with maximum deviations from the mean discharge of not more than 10 % of the mean discharge (second bar-chart, Fig. 43) could be obtained to an equal dilution requirement along the diffuser. Due to different pressure losses along the diffuser pipe and the port/riser configurations (line in second bar-chart, Fig. 43) the discharge is decreasing typically to the

seaward end, which can be prevented by modifying the geometries along the diffuser. In this case by reducing the main diffuser diameter to the seaward end.
The use of *duckbill valves* provides a more homogeneous flow distribution especially for low flows (Fig. 43 and Fig. 44, right). Without duckbills the flow distribution is unaffected by changing the total flow due to neglectable density differences between the effluent and the ambient and the almost horizontal installation of the diffuser (Fig. 44, first chart, left). But the total head (TH) necessary to drive the system is higher with duckbill valves (Fig. 44, legend). Larger duckbills (200 mm) reduce the total head almost to the level without duckbills, but decrease also the effects on the discharge distributions to negligible levels. Changes in the ambient water level do not have any effect on the flow characteristics but increase the total head.
To prevent intrusion of ambient water (including sediments), especially during low flow, the port densimetric Froude number should be bigger than unity: $F_p = V_p/(\Delta\rho/\rho g D_p)^{0,5} > 1$ (Wilkinson, 1988), where V_p denotes the port exit velocity and D_p the port diameter. This gives a critical port velocity $V_{p,crit} = (\Delta\rho/\rho g D_p)^{0,5} = 0.041$ m/s for Berazategui. All port and jet exit velocities (third bar-chart, Fig. 43, Fig. 44) are considerably higher for all applied flowrates. Duckbill valves cause additionally a homogenization of the jet exit velocities (Fig. 43, third bar-chart, Fig. 44, fourth bar-chart). Scouring velocities above 0.5 m/s are obtained for almost the whole diffuser section. (Fig. 43, fouth bar-chart, Fig. 44, fifth bar-chart)

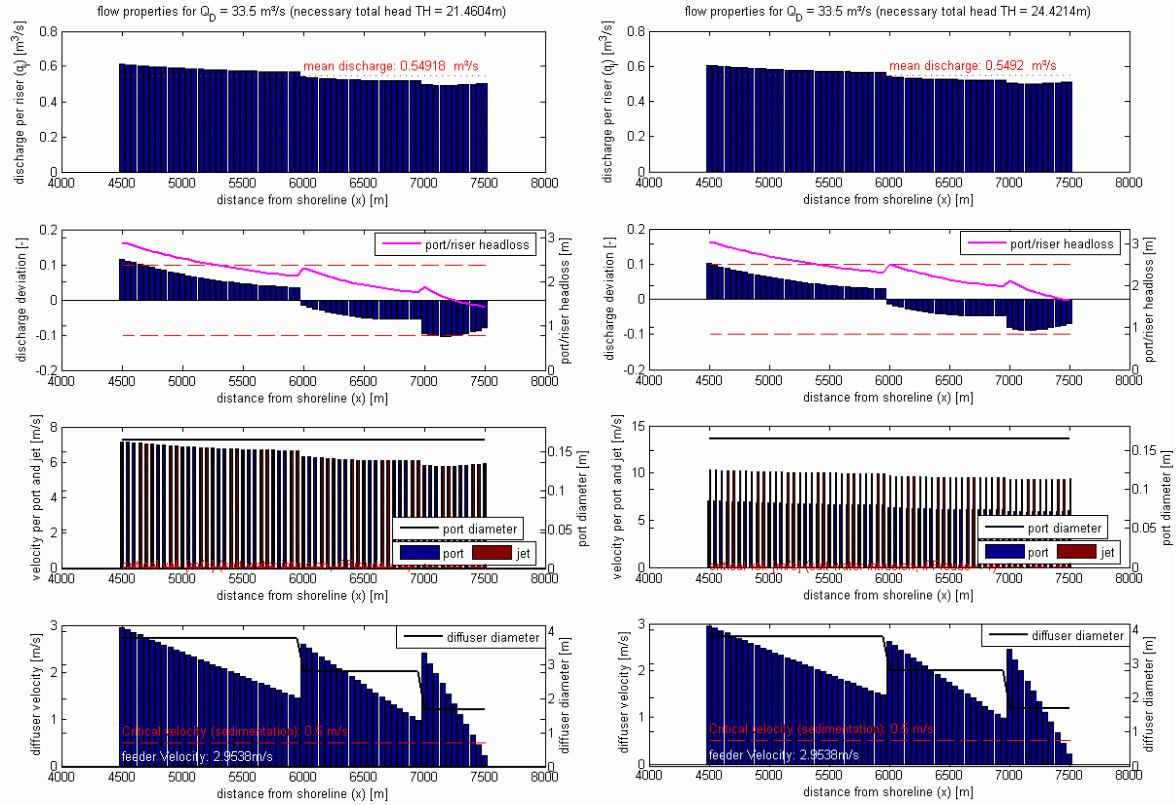

flow properties for Q_D = 33.5 m³/s (necessary total head TH = 21.4604m)
flow properties for Q_D = 33.5 m³/s (necessary total head TH = 24.4214m)
discharge per riser (q_r) [m³/s]
mean discharge: 0.54918 m³/s
mean discharge: 0.5492 m³/s
distance from shoreline (x) [m]
discharge deviation [-]
port/riser headloss
port/riser headloss [m]
velocity per port and jet [m/s]
port diameter
port
jet
port diameter [m]
diffuser velocity [m/s]
diffuser diameter
diffuser diameter [m]
Critical velocity (sedimentation): 0.5 m/s
feeder Velocity: 2.9538m/s

Fig. 43: Flow characteristics for final design at maximum flow: left column without and right with Duckbill Valves. Top-down: Individual riser flow distribution along diffuser, riser flow deviation from mean, losses in port/riser configurations (line), port and jet discharge velocities and diffuser pipe velocities, port and diffuser diameter (lines).

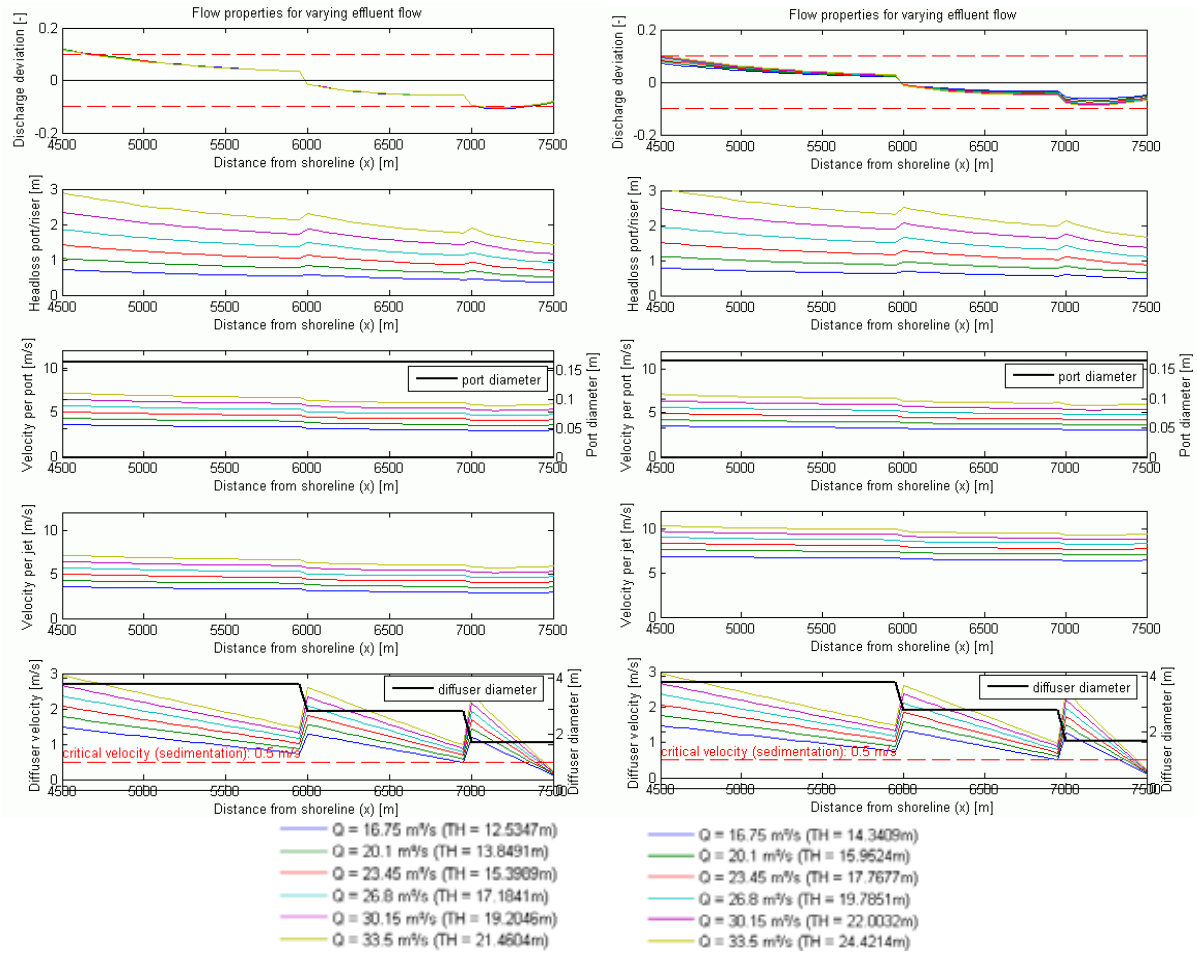

Flow properties for varying effluent flow
Discharge deviation [-]
Distance from shoreline (x) [m]
Headloss port/riser [m]
Velocity per port [m/s]
port diameter
Port diameter [m]
Velocity per jet [m/s]
Diffuser velocity [m/s]
diffuser diameter
Diffuser diameter [m]
critical velocity (sedimentation): 0.5 m/s
Q = 16.75 m³/s (TH = 12.5347m)
Q = 20.1 m³/s (TH = 13.8491m)
Q = 23.45 m³/s (TH = 15.3989m)
Q = 26.8 m³/s (TH = 17.1841m)
Q = 30.15 m³/s (TH = 19.2046m)
Q = 33.5 m³/s (TH = 21.4604m)
Q = 16.75 m³/s (TH = 14.3409m)
Q = 20.1 m³/s (TH = 15.9524m)
Q = 23.45 m³/s (TH = 17.7677m)
Q = 26.8 m³/s (TH = 19.7851m)
Q = 30.15 m³/s (TH = 22.0032m)
Q = 33.5 m³/s (TH = 24.4214m)

Fig. 44: Flow characteristics for the final design, for different discharges (Q), showing the riser flow deviation, port/riser headloss, port and jet discharge velocities, diffuserpipe velocities (left without duckbills, right with duckbills) and total head (TH)

An increasing inflow or increasing ambient water level mainly increase the total head (Fig. 45). Headwork storage tanks should be capable to manage these changes. For slowly increasing future flows an extension of storage tanks can be done only when necessary saving investment costs for the commissioning.

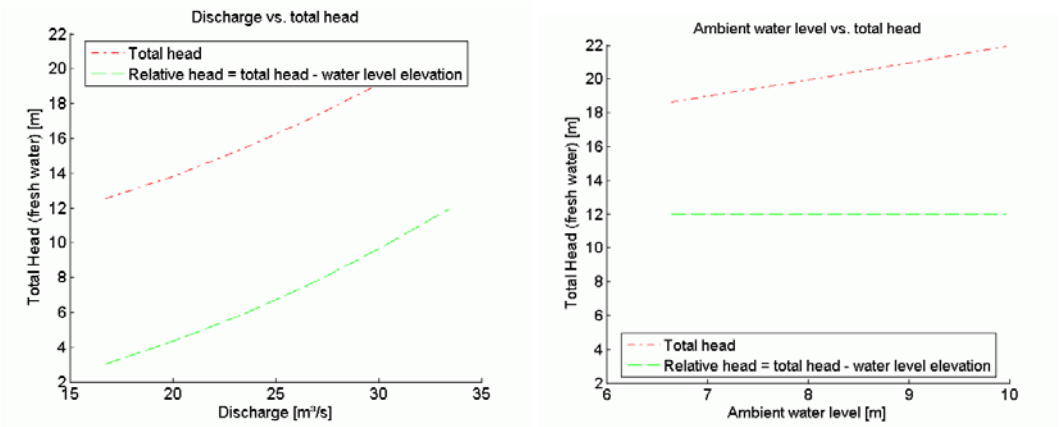

Discharge vs. total head
Total head
Relative head = total head - water level elevation
Total Head (fresh water) [m]
Discharge [m³/s]
Ambient water level vs. total head
Ambient water level [m]

Fig. 45: Changes in total head for varying discharges vs. constant ambient water level (left) or maximum discharge vs. varying water level (right).

Especially for this long diffuser a strong influence of the local loss formulations on the discharge profile has been observed. Precautious analysis and further sensitivity analysis allowed to evaluate whether parameter changes are in acceptable orders, which has been the case for Berazategui outfall.

8 Conclusions

Calculations for the internal manifold hydraulics show a strong sensitivity on the representation and formulation of local losses even for relatively simple riser/port configurations. Special attention is necessary to account for all these losses in multiport diffuser design, a fact that is often neglected in common programs causing malfunction resulting in different total heads, bad discharge distributions, and sediment accumulation.

CorHyd design procedure including CorHyd calculations consider flowrate variations either for short term or long term changes and allow to optimize the diffuser geometry to comply with scouring of sediments under minimal headloss conditions and a homogeneous discharge distribution required from the environmental impact criterias. Proper diffuser performance is therefore assured for most of the boundary conditions often with cheaper maintenance and operation costs. Latter can be achieved by reducing the sedimentation of particles in the diffuser and therefore the cleaning intervals and also a time dependend diffuser extension, where fewer pumps are needed at the commission.

The presented applications here, release some assumptions of previous ‘diffuser programs’ by considering flexible geometry specifications with high risers and variable area orifices, all with implemented additional local losses occurring in the manifold.

9 References

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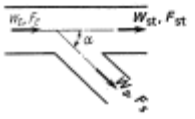
10 Annex

10.1 Local loss formulations: Division of flow (Idelchik)

Diverging wye of the type $F_s + F_{st} > F_c$; $F_{st} = F_c$; $\alpha = 0$–$90°$. Side branching. [10] — Diagram 7-15



h_s is the height of the cross section of the side branch; h_c is the height of the cross section of the common straight channel

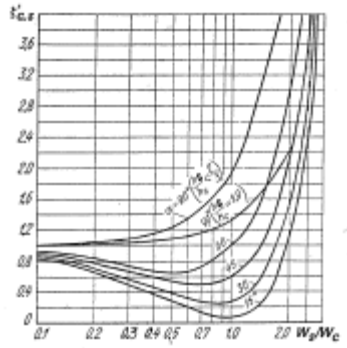
1. $0 < \alpha < 60°$ and $\alpha = 90°$ at $h_s/h_c \leq 2/3$:

$$\zeta_{c.s} = \frac{\Delta p_s}{\rho w_c^2/2} = A' \left[1 + \left(\frac{w_s}{w_c}\right)^2 - 2\frac{w_s}{w_c}\cos\alpha\right] = A'\zeta'_{c.s}$$

2. $\alpha = 90°$ and $h_s/h_c = 1.0$ (up to $w_s/w_c \approx 2.0$):

$$\zeta_{c.s} = \frac{\Delta p_s}{\rho w_c^2/2} = A' \left[1 + 0.3\left(\frac{w_s}{w_c}\right)^2\right] = A'\zeta'_{c.s}$$

where for $\zeta'_{c.s}$, see the curves $\zeta'_{c.s} = f(w_s/w_c)$ at different α; for A', see paragraph 15.



$$\zeta_s = \frac{\Delta p_s}{\rho w_s^2/2} = \frac{\zeta_{c.s}}{(w_s/w_c)^2}$$

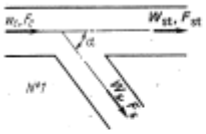
$$\frac{w_s}{w_c} = \frac{Q_s}{Q_c}\frac{F_c}{F_s}$$

Values of $\zeta'_{c.s}$

$\frac{w_s}{w_c}$	α, °				$\alpha = 90°$	
	15	30	45	60	$h_s/h_c \leq 2/3$	$h_s/h_c = 1.0$
0	1.0	1.0	1.0	1.0	1.0	1.0
0.1	0.82	0.84	0.87	0.91	1.01	1.0
0.2	0.65	0.70	0.75	0.84	1.04	1.01
0.4	0.38	0.46	0.60	0.76	1.16	1.05
0.6	0.20	0.31	0.50	0.65	1.35	1.11
0.8	0.09	0.25	0.51	0.80	1.64	1.19
1.0	0.07	0.27	0.58	1.00	2.00	1.30
1.2	0.12	0.36	0.74	1.23	2.44	1.43
1.4	0.24	0.70	0.98	1.54	2.96	1.59
1.6	0.46	0.80	1.30	1.98	3.54	1.77
2.0	1.10	1.52	2.16	3.00	4.60	2.20
2.6	2.75	3.23	4.10	5.15	7.76	–
3.0	7.20	7.40	7.80	8.10	9.00	–
4.0	14.1	14.2	14.8	15.0	16.0	–
5.0	23.2	23.5	23.8	24.0	25.0	–
6.0	34.2	34.5	35.0	35.0	36.0	–
8.0	62.0	62.7	63.0	63.0	64.0	–
10	98.0	98.3	98.6	99.0	100	–

Diverging wye of the type $F_s + F_{st} > F_c$ and $F_s + F_{st} = F_c$;
$\alpha = 0$–$90°$. Passage [10]

Diagram
7-17

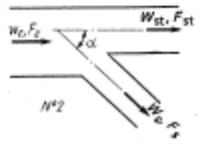


No. 1. $F_s + F_{st} > F_c$ at $w_{st}/w_c \leq 1.0$:

$$\zeta_{c,st} = \frac{\Delta p_{st}}{\rho w_c^2/2} \approx 0.4 \left(1 - \frac{w_{st}}{w_c}\right)^2$$

1. Values of $\zeta_{c,st}$

$\frac{w_{st}}{w_c}$	$\alpha = 15$–$90°$ at $F_{st}/F_c = 0$–1.0
0	0.40
0.1	0.32
0.2	0.26
0.3	0.20
0.4	0.14
0.5	0.10
0.6	0.06
0.8	0.02
1.0	0



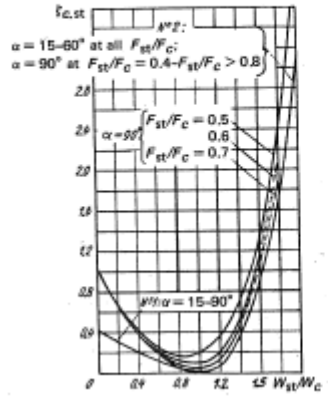
No. 2. $F_s + F_{st} = F_c$ at $w_{st}/w_c \geq 1.0$:

$$\zeta_{c,st} = \frac{\Delta p_{st}}{\rho w_c^2/2}$$

see the curves $\zeta_{c,st} = f(w_{st}/w_c)$:

$$\zeta_{st} = \frac{\Delta p_{st}}{\rho w_{st}^2/2} = \frac{\zeta_{c,st}}{(w_{st}/w_c)^2}$$

$$\frac{w_{st}}{w_c} = \frac{Q_{st}}{Q_c}\frac{F_c}{F_{st}}$$

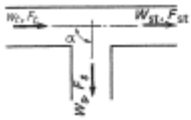


Values of $\zeta_{c,st}$

	α					
	15–60°	90°				
	F_{st}/F_c					
$\frac{w_{st}}{w_c}$	0–1.0	0–0.4	0.5	0.6	0.7	>0.8
0	1.00	1.00	1.00	1.00	1.00	1.00
0.1	0.81	0.81	0.81	0.81	0.81	0.81
0.2	0.64	0.64	0.64	0.64	0.64	0.64
0.3	0.50	0.50	0.52	0.52	0.50	0.50
0.4	0.36	0.36	0.40	0.38	0.37	0.36
0.5	0.25	0.25	0.30	0.28	0.27	0.25
0.6	0.16	0.16	0.23	0.20	0.18	0.16
0.8	0.04	0.04	0.17	0.10	0.07	0.04
1.0	0.00	0.00	0.20	0.10	0.05	0.00
1.2	0.07	0.07	0.36	0.21	0.14	0.07
1.4	0.39	0.39	0.79	0.59	0.39	–
1.6	0.90	0.90	1.40	1.16	–	–
1.8	1.78	1.78	2.44	–	–	–
2.0	3.20	3.20	4.00	–	–	–

Threaded wyes of the type $F_g + F_c > F_c$; $F_{st} = F_c$; made of malleable iron; $\alpha = 90°$ [2]

Diagram 7-18



Side branch

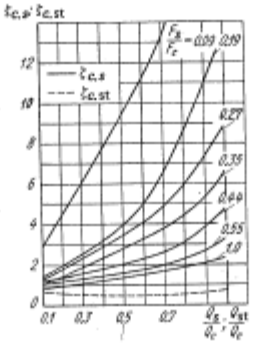
$$\zeta_{c.s} = \frac{\Delta p_g}{\rho w_g^2/2}$$, see the curves $\zeta_{c.s} = f(Q_g/Q_c)$ at different F_g/F_{st};

$$\zeta_g = \frac{\Delta p_g}{\rho w_g^2/2} = \frac{\zeta_{c.s}}{(Q_g F_c/Q_c F_g)^2}$$

Straight passage

$$\zeta_{c.st} = \frac{\Delta p_{st}}{\rho w_c^2/2}$$, see the curve $\zeta_{c.st} = f(Q_{st}/Q_c)$ at all F_g/F_c;

$$\zeta_{st} = \frac{\Delta p_{st}}{\rho w_{st}^2/2} = \frac{\zeta_{c.st}}{(1 - Q_g/Q_c)^2 (F_c/F_{st})^2}$$



Values of $\zeta_{c.s}$ and $\zeta_{c.st}$

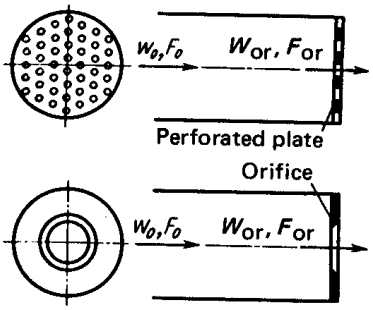
F_g/F_c	Q_g/Q_c (Q_{st}/Q_c) 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
					Values of $\zeta_{c.s}$					
0.09	2.80	4.50	6.00	7.88	9.40	11.1	13.0	15.8	20.0	24.7
0.19	1.41	2.00	2.50	3.20	3.97	4.95	6.50	8.45	10.8	13.3
0.27	1.37	1.81	2.30	2.83	3.40	4.07	4.80	6.00	7.18	8.90
0.35	1.10	1.54	1.90	2.35	2.73	3.22	3.80	4.32	5.28	6.53
0.44	1.22	1.45	1.67	1.89	2.11	2.38	2.58	3.04	3.84	4.75
0.55	1.09	1.20	1.40	1.59	1.65	1.77	1.94	2.20	2.68	3.30
1.00	0.90	1.00	1.13	1.20	1.40	1.50	1.60	1.80	2.06	2.80
					Values of $\zeta_{c.st}$					
At all F_g/F_c	0.70	0.64	0.60	0.57	0.55	0.51	0.49	0.55	0.62	0.70

10.2 Local loss formulations: Orifices (Idelchik)

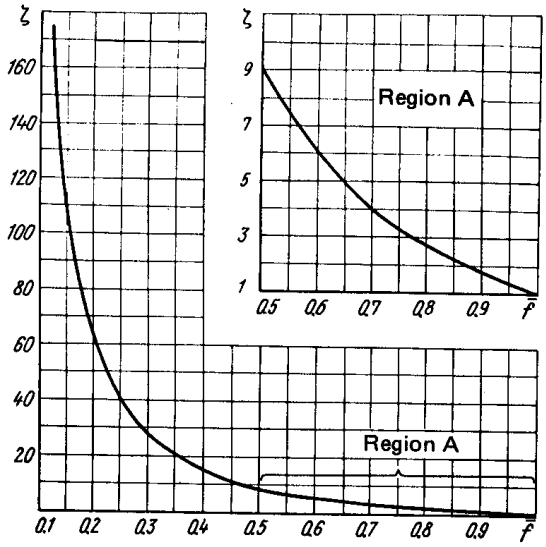
Discharge from a straight tube through an orifice or a perforated plate (grid) with sharp-edged orifices ($l/d_h = 0$–0.015); $\mathrm{Re} = w_{or} d_h/\nu \geq 10^5$ [14–16]

Diagram 11-18

$$\zeta = \frac{\Delta p}{\rho w_0^2/2} = (1 + 0.707\sqrt{1-\bar{f}})^2 \frac{1}{\bar{f}^2}, \text{ see the graph}$$



$$d_h = \frac{4f_0}{\Pi_{or}}$$



$\bar{f}$	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
ζ	1140	280	122	67	41.6	30.0	20.2	15.0	11.5

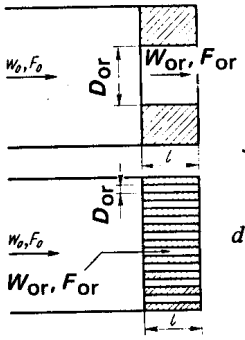
$\bar{f}$	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.9	1.0
ζ	9.00	7.40	6.20	4.80	3.90	3.30	2.70	2.22	1.80	1.0

Discharge from a straight tube through an orifice or a perforated plate (grid) with differently shaped orifice edges; $Re = w_{or} d_h/\nu > 10^4$ [14–16]

Scheme and graph

Resistance coefficient

$$\zeta = \frac{\Delta p}{\rho w_0^2/2}$$



$$\bar{f} = \frac{F_{or}}{F_0}$$

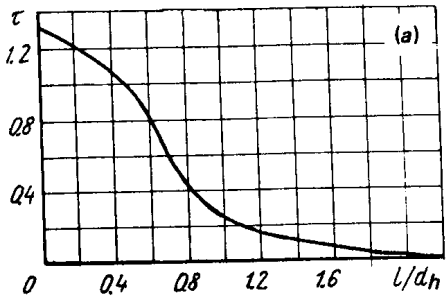
$$d_h = \frac{4 f_0}{\Pi_{or}}$$

$$\zeta = \left\{[1 + 0.5(1 - \bar{f}) + \tau\sqrt{1 - \bar{f}}] + \lambda \frac{l}{d_h}\right\} \frac{1}{\bar{f}^2}$$

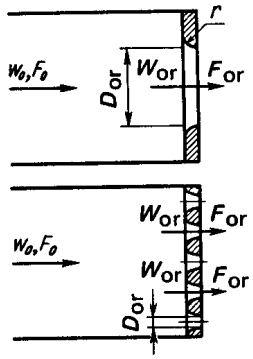
$$= \left(\zeta_0 + \lambda \frac{l}{d_h}\right) \frac{1}{\bar{f}^2}$$

where $\zeta_0 = 1 + 0.5(1 - \bar{f}) + \tau\sqrt{1 - \bar{f}}$; for λ, see Diagrams 2-1 through 2-6; $\tau = f(l/d_h)$

Thick walled orifices



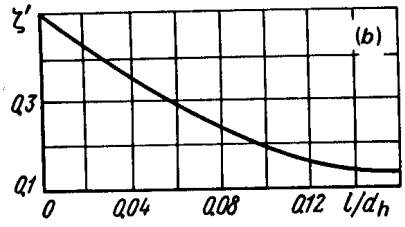
$\frac{l}{d_h}$	0	0.2	0.4	0.6	0.8
τ	1.35	1.22	1.10	0.84	0.42
$\frac{l}{d_h}$	1.0	1.2	1.6	2.0	2.4
τ	0.24	0.16	0.07	0.02	0



$$\zeta = [1 + \sqrt{\zeta'(1 - \bar{f})}]^2 \frac{1}{\bar{f}^2}$$

where $\zeta' = f(l/d_h)$

Orifice edges beveled in the flow direction



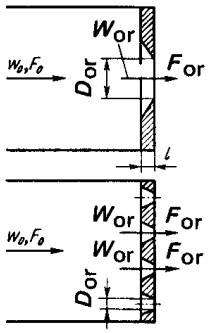
$\frac{l}{d_h}$	0.01	0.02	0.03	0.04
ζ'	0.46	0.42	0.38	0.35
$\frac{l}{d_h}$	0.06	0.08	0.12	0.16
ζ'	0.29	0.23	0.16	0.13

Discharge from a straight tube through an orifice or a perforated plate (grid) with differently shaped orifice edges; $\mathrm{Re} = w_{or} d_h/\nu > 10^4$ [14-16] — Diagram 11-19

Scheme and graph

Resistance coefficient

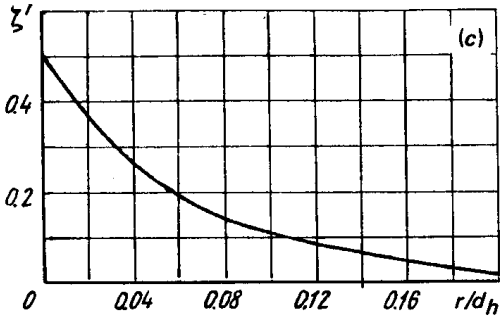
$$\zeta = \frac{\Delta p}{\rho w_0^2/2}$$



$$\zeta = [1 + \sqrt{\zeta'(1-\bar{f})}]^2 \frac{1}{\bar{f}^2}$$

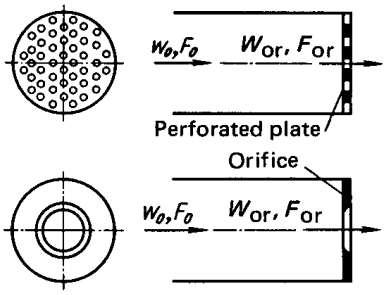
where $\zeta' = f\left(\frac{r}{d_h}\right)$

Orifice edges rounded in the flow direction



$\frac{r}{d_h}$	0	0.01	0.02	0.03	0.04	0.05
ζ'	0.50	0.44	0.37	0.31	0.26	0.22
$\frac{r}{d_h}$	0.06	0.08	0.12	0.16	0.20	
ζ'	0.19	0.15	0.09	0.06	0.03	

Discharge from a tube through an orifice or a perforated plate (grid) with differently shaped orifice edges in transition and laminar regions ($\mathrm{Re} = w_{or} D_h/\nu < 10^4$–$10^5$, tentatively) [14-16] — Diagram 11-20



$$D_h = \frac{4F_{or}}{\Pi_{or}}$$

$$\bar{f} = \frac{F_{or}}{F_0}$$

1) $25 < \mathrm{Re} < 10^4$–10^5:

$$\zeta = \frac{\Delta p}{\rho w_0^2/2} = \zeta_\phi \frac{1}{\bar{f}^2} + \bar{\epsilon}_{0\,\mathrm{Re}} \zeta_{qu}$$

2) $10 < \mathrm{Re} < 25$:

$$\zeta = \frac{33}{\mathrm{Re}} \frac{1}{\bar{f}^2} + \bar{\epsilon}_{0\,\mathrm{Re}} \zeta_{qu}$$

3) $\mathrm{Re} < 10$:

$$\zeta = \frac{33}{\mathrm{Re}} \frac{1}{\bar{f}^2}$$

where $\bar{\epsilon}_{0\,\mathrm{Re}} = f_2(\mathrm{Re})$ and $\zeta_\phi = f_1(\mathrm{Re}, F_0/F_1)$, see Diagram 4-19 (it is assumed that $\bar{f} = F_{or}/F_0$ corresponds to F_0/F_1); ζ_{qu} is determined as at $\mathrm{Re} > 10^4$–10^5 from Diagrams 11-18 and 11-19.